High Voltage

Content

Ch(1) Introduction

Voltage Stress on dielectrics

During **Normal Operation** the insulator is subjected to electrical stresses due to

1- Contamination Defects
2- Transient over voltage due to (Lighting – Switching)

So when we **Design Insulators** we study :

1- Voltage Stress which insulation can withstand
2- Response of insulating materials when subjected to these stresses

Types of insulating materials

1- **Gas** (Air, SF6, N2, Co2, …)
   - Most used due to **self-restoring capability**
2- **Liquid** (Oil,…)
   - non-self-restoring capable
3- **Solid**
   -if it breaks down the insulation is replaced entirely.

Ch(2) Break down in gases

Atoms Exist in three states

Normal State	Excited State	Ionized Atom
-The Atom is stable -No.Electrons=No.Protons	- not stable - has gained energy but not enough to free an electron so, the electron goes back to get the atom stable again in period called $\boldsymbol{life\ time\ = 10^{-8}\ s}$ **<u>Meta Stable Atom</u>** Excited but with a life time of $\boldsymbol{life\ time}\ = 0.1{\sim}10^{-3}\ s$	-The atom has gained enough energy to free the electron -the atom turns into a **Positive Ion**

Electrons : tiny ,light -ve ; **protons** : large +ve ; **neutrons** : large no ch ; **photon** : no mass no charge

When electrons move between energy level they absorb or emit <u>photons</u> with magnitude defined energy levels the electrons can acquire in the atoms.

Negative ions : when elevtron attached to neutral atom or moelcule

<u>(1) Break Down Stages</u>

(1)[1] Ionization Process

Classified into:
Primary Process : occurs in the gas itself
Secondary Process : occurs in the cathode surface (Cathode Process)

Types of Ionization

1-Ionization By Collision

$$e^- + A \xrightarrow{\Delta\omega > \omega_i} A^+ + e^- + e^-$$

$$e^- + A \xrightarrow{\Delta\omega < \omega_i} A^* + e^-$$

$$\Delta\omega : energy\ gained\ from\ collision$$
$$\omega_i : energy\ required\ for\ ionization\ to\ happen$$

$$\Delta\boldsymbol{\omega} \propto \frac{\boldsymbol{E}}{\boldsymbol{P}}$$

Note:
- Ionization increase with voltage or electric field which causes Break down
- Ionization decreases with increase in pressure ; that's why we use high pressure gases in insulation

Two Parameters

$$\sigma : collision\ cross\ section : area\ collison\ occurs \quad \sigma = \pi(r_e + r_a)^2$$

$$\bar{\lambda} : collision\ mean\ free\ path : between\ 2\ successive\ collisions\ \bar{\lambda} = \frac{1}{\sigma N} = \frac{1}{\pi N(r_e + r_a)^2}$$

$$P \uparrow \quad N \uparrow \bar{\lambda} \downarrow$$

During travel $\Delta W = QV = eE\bar{\lambda}$ $,\bar{\lambda} \propto \frac{1}{P}$ $\therefore \Delta W \propto \frac{E}{P}$

2-Photo Ionization

A)
1-Excited Atom turns to stable state and emits **photons 2-**Cosmic ,x-rays (continuos)

Other Atoms will absorb **these photons** and if it has enough energy it will ionize the atom

(Primary Ionization Process)

$$e^- + K_e + A \xrightarrow{\Delta\omega > \omega_i} e^- + A^*$$

$$A^* \rightarrow A + h\,\nu$$

$$h\nu + A \xrightarrow{h\nu \geq \omega_i} A^+ + e^-$$

condition :

$$h\nu \geq \omega_i \quad \Rightarrow \frac{hc_0}{\lambda} \geq \omega_i$$

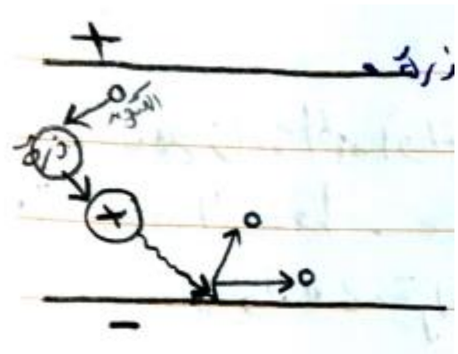
$$\boldsymbol{\lambda \leq \frac{C_0 h}{\omega_i}} \quad [\ \boldsymbol{Condition\ for\ photo\ ionization}]$$

B)
if the photon hits the cathode surface and it emits an electron it's
(Secondary Ionization Process)

$$h\nu \geq \phi\ [Condition\ for\ secondary\ ionization]$$

$$\phi : Work\ Function\ ; needed\ energy\ to\ emit\ an\ electron\ out\ of\ the\ solid\ material$$

3- Ionization by +ve ion impact



The Positive ion hits the cathode surface emitting **2 electrons**

First for neutralization of the atom

Second for the ionization process to continue

$$\boldsymbol{KE + \omega_i \geq 2\phi} \quad \text{"}\boldsymbol{Condition}\text{"}$$

Main **Secondary** Process

4- Ionization by metastable atom

$A^m + B \xrightarrow{\omega^m > \omega_i} A + B^+ + e^- \ (Primary)$ // if it hits the cathode (secondary)

5-Thermal Ionization

At high temp -> KE -> ionization (Flames , High pressure arcs)

Some recombine

$$A + W_t \leftrightarrow A^+ + e^-$$

If there is **no electric field to drive the electrons** then electrons will combine with positive ions again

(Thermal Dynamic Equilibrium)

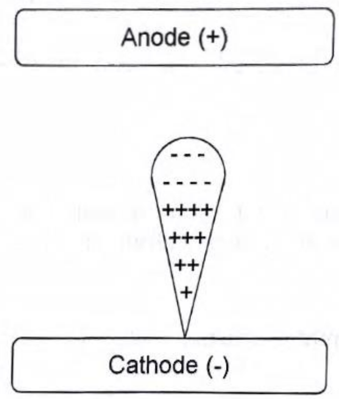
(1)[2] Pre-Breakdown in Gases

- depends on two stages

(a) Generation of electron Avalanche:

(Only Primary Ionization Effect)

- Depends on electrons collisions, every electron goes toward the Anode and every +ve ion goes toward the cathode causing the **Avalanche**



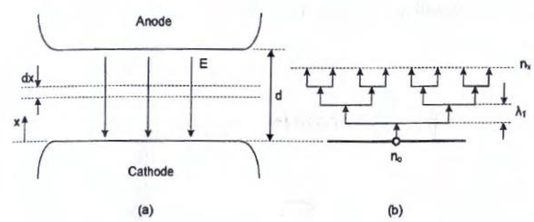
Calculate Current at distance x from the cathode surface

$$I = I_0 e^{\alpha x} \quad , \quad n = n_0 e^{\alpha x} \quad , \frac{n}{t} = \frac{I}{e^-} \; cuz \; I_o = \frac{Q}{t} = \frac{ne^-}{t}$$

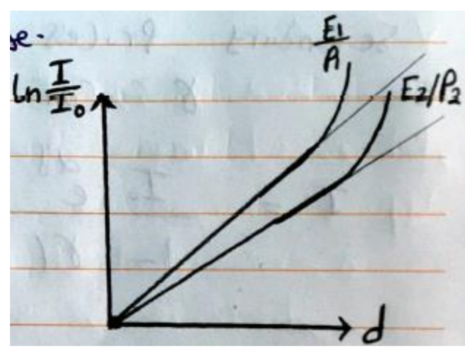
Where :

$n_0, I_0 \rightarrow initial\ number\ of\ electrons\ at\ cathode\ surface$
$\alpha \rightarrow First\ townsend\ ionization\ coefficient \propto E/p$

$x \; \rightarrow distance\ from\ cathode$



$$\because \alpha \propto \Delta\omega \quad ; \quad \Delta\omega \propto \frac{E}{P}$$
$$\therefore \alpha \propto \frac{E}{P}$$



Proof

$$dn_x = \alpha n_x dx$$

$$\frac{dn_x}{n_x} = \alpha d_x$$

$$solve\ ODE: \; \ln n_x = \alpha\, x + C$$
$$from\ initial\ x = 0 \; n_x = n_0 \quad C = \ln n_0$$

$$\therefore \boldsymbol{n_x = n_0 e^{\alpha x}}$$
$$\boldsymbol{also, I_x = I_o\, e^{\alpha x}}$$

(b) current growth considering secondary process

- such as (+ve Ion,Photon,MetaStable)

$$n_d = \frac{n_0\ e^{\alpha d}}{1-\gamma(e^{\alpha d}-1)}$$

Where

$$\gamma: second\ townsend\ ionization\ coeffiecient$$

$$I_d = \frac{I_0 e^{\alpha d}}{1-\gamma(e^{\alpha d}-1)}$$

Proof

$$n'_o = secondary\ elec.produced\ at\ cathode$$
$$n''_o = total\ num\ of\ elec\ leaving\ cathode$$
$$n''_o = n'_o + n_o \ \rightarrow\ n'_o = \ n''_o - n_o$$

$$so\ \ n'_o = \gamma\ n''_o(e^{\alpha d}-1)$$

$$n''_o = \frac{n_o}{1-\gamma(e^{\alpha d}-1)}$$

$$so\ electrons\ reaching\ anode\ \ n_d = n''_o\ e^{\alpha d}$$

$$so$$

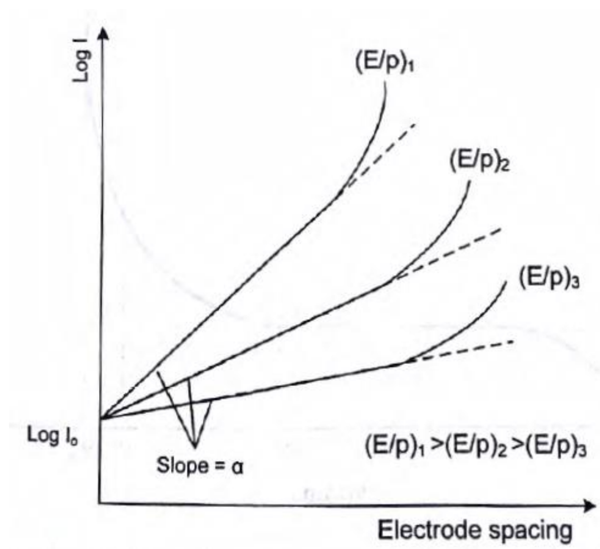
$$n_d = \frac{n_o\ e^{\alpha d}}{1-\gamma(e^{\alpha d}-1)}$$

$$I_d = \frac{I_o\ e^{\alpha d}}{1-\gamma(e^{\alpha d}-1)}$$

To determine α and γ

1- A graph is plotted against distance between electrodes (gap)
2- For given E and P (const) **the slope of straight line is $\boldsymbol{\alpha}$**
3- At high voltages the current increases due to secondary process
   so, we can calculate γ from

$$I = \frac{I_0 e^{\alpha d}}{1-\gamma(e^{\alpha d}-1)}$$



(1)[3] Breakdown

Break Down Mechanisms in Gases

(1) Townsend Mechanism [Uniform Field][Low Pd]

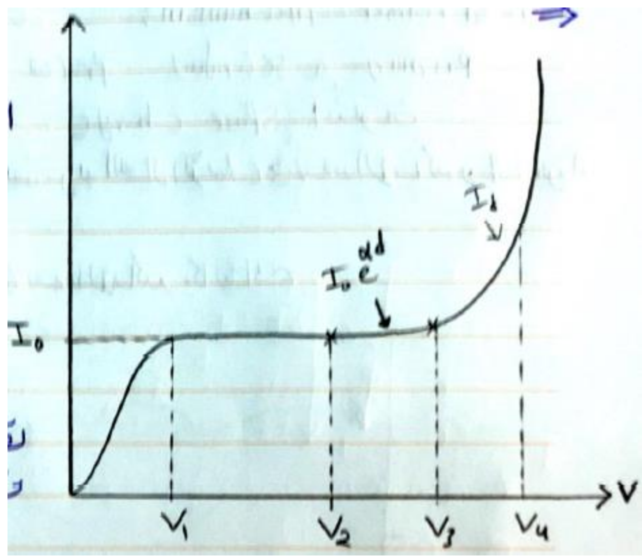
Breakdown occurs when current is infinity this means

$$1-\gamma\left(e^{\alpha d}-1\right)=0$$

$$\therefore e^{\alpha d} \gg 1$$
$$\therefore \boldsymbol{\gamma e^{\alpha d}-1 \;=0}$$
$$(\boldsymbol{condition\ of\ townsend\ mechanism})$$

$$Factors\ that\ cause\ Breakdown$$
$$P, E, d, type\ of\ insualtion$$

- **Variation of gap current with applied voltage by townsend**



$$0 \rightarrow V_1$$

Current increases due to cathode electrons until it stops at I_0

$$V_1 \rightarrow V_2$$

Stops at I_0(saturation current)

$$V_2 \rightarrow V_3$$

Electrons energy is now enough to cause ionization and current increases

$$V_4 \rightarrow$$

Break down happens and current increases with large value and it’s called **Breakdown Voltage**

(2) Streamer Mechanism [Uniform Field][High Pd]

Townsend didn't consider **Space Charge**

Space Charge

- will <u>increase</u> original field in some areas , <u>increase</u> ionization
- will <u>decrease</u> original field in some areas , <u>decrease</u> ionization

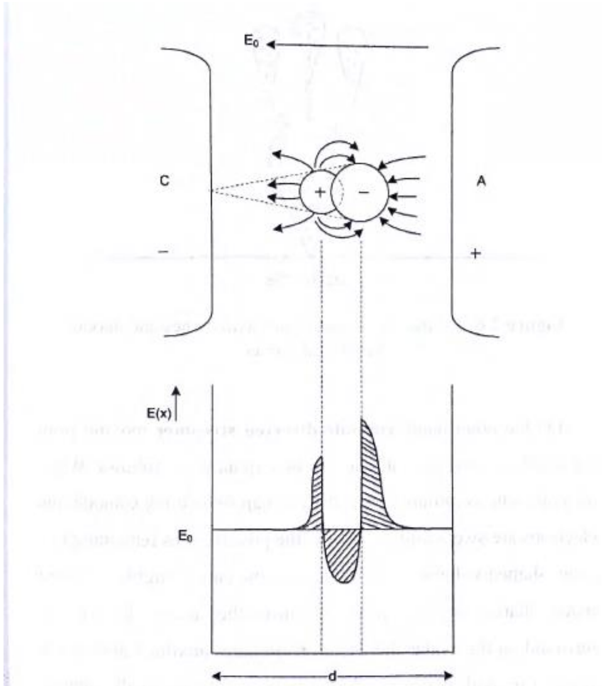


Figure 2.5: Representation of field distortion in a gap caused by space charge of an electron avalanche

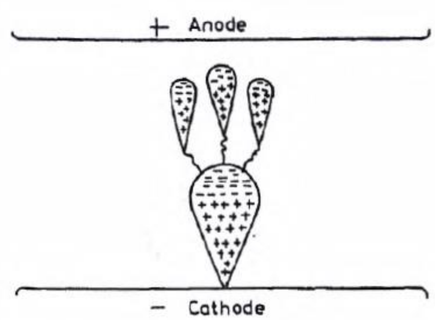


Figure 2.6: Formation of secondary avalanches and anode-directed streamer

- **Anode Directed Streamer(-ve Streamer)**

After avalanche and space charge , it will **cause <u>Auxiliary Avalanche directed to Anode</u>**

- **Cathode Directed Streamer (+ve Streamer)**

Here electrons move **fast** towards <u>Anode</u>

But +ve Ions move **Slowly** towards the <u>Cathode</u>

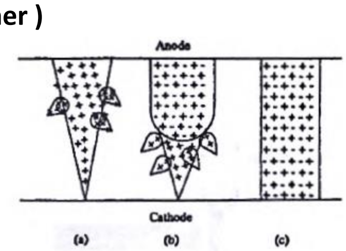
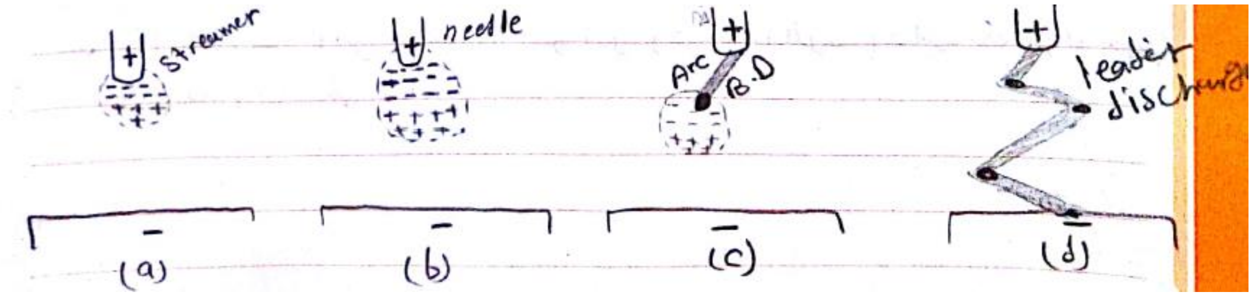


Figure 2.7: Cathode-directed streamer

(3) Leader Mechanism [Non-Uniform Field]

The **Electric Field** changes with the distance from the Anode
- **Strongest** at the source , - **Weakest** at the other pole (cathode (ground))

<u>Note:</u> in long gaps ; if the voltage at the stressed electrode exceeds the **Coronal Level** , <u>The gap is ionized</u>



Ionization in the form of streamer

1- (-ve) charges move toward electrode and (+ve) charges move far
2- With high field concentration, Breakdown occurs in the form of <u>arcing</u>
3- At the tip of channel , <u>a new streamer is initiated</u> and so on until breakdown reaches the other electrode

<u>Conclusion :-</u>

Leader mechanism occurs in case of large gap & non-uniform field.

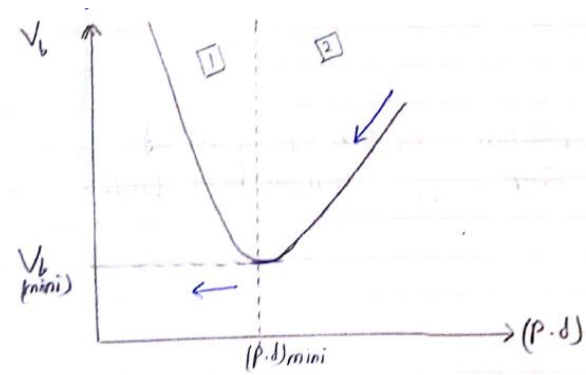
From Townsend Condition for B.D $\gamma[e^{\alpha d}-1\,]=1$

$$\alpha = F_1\left(\frac{E}{P}\right) \qquad ,\gamma = F_2\left(\frac{E}{P}\right)$$

$$\therefore F_2\left(\frac{E}{P}\right)\ \left[e^{F_1\left(\frac{E}{P}\right)}-1\right]=1 \qquad ,but\ E=\frac{V_b}{d} \quad ;V_b{:}\,B.D\ voltage$$

$$\therefore F_2\left(\frac{V_b}{P.d}\right)\left[\,e^{F_2\left(\frac{V_b}{P.d}\right)}-1\right]=1$$

$$\therefore V_b\ must\ be\ function\ of\ (P.d)$$



$$when\ [P.d]\downarrow\ \ then\ \ V_b\downarrow \quad\ and\ that's\ logical$$
$$but, after\ [P.d]_{Min}$$
$$[P.d]\downarrow\ \ then\ \ V_b\uparrow$$

That's because:

- When the gap distance is very small the electrons move from Anode toward Cathode without any collisions so we need high breakdown voltage
- If pressure is so small number of atoms is so small so not enough to produce electrons for ionization.

Electronegative gases

Gases that has a large capability of absorbing electrons to produce **(–ve ions)** **ex: SF6**

(**<u>Electron Attachment)</u>**

So the chance of B.D is low and we need higher breakdown voltage

$$\alpha \rightarrow Ionization\ Coefficient \quad \eta \rightarrow attachment\ coefficient$$

Condition for Breakdown is

$$\frac{\gamma\alpha}{\alpha-\eta}\left[e^{(\alpha-\eta)d}-1\right]=1$$

$$if\ \alpha<\eta \rightarrow B.D \quad Not\ Occur$$
$$if\ \alpha>\eta \rightarrow B.D\ \ Occurs$$

Critical Case

$$if\ e^{\alpha-\eta} \ll 1 \quad \therefore \frac{\gamma\alpha}{\alpha-\eta}[0-1]=1$$

$$\gamma\ small\ can\ be\ neglected\ , depends\ on \frac{E}{p}\ and\ sets\ lower\ limit$$

$$\alpha=\frac{\eta}{1+\gamma}$$

$$\therefore \boldsymbol{\alpha}=\boldsymbol{\eta} \quad [Critical\ Case\ (Beginning\ of\ B.D)]$$

Breakdown under corona discharge

If the field is uniform , if you increase field (by increasing voltage) <u>, Break down happens directly</u>

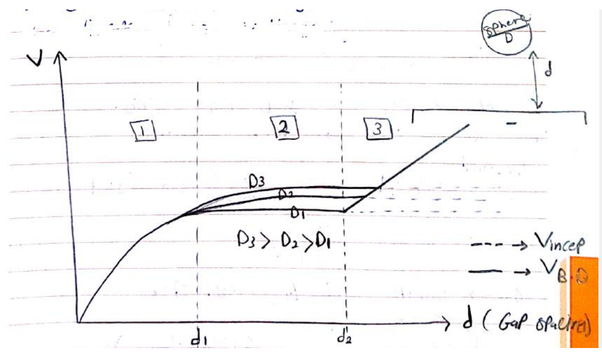
If the field is non-uniform , if you increase field (by increasing voltage),<u> Partial Discharge happens</u>

That **Partial discharge** is called <u>Corona discharge</u> is accompanied with noise (zzzz) and light(spark)

And then with more increasing the Breakdown happens

So in non-uniform field we measure 2 voltages
1- Corona inception voltage

2-Breakdown Voltage



Region (1)

- The gap spacing is very small so the field seems **uniform**
- The Diameter won't affect cause the gap distance is very small
- So no difference between V_{incep} and V_{BD}

Region (2)

- <u>Small Diameter</u> it will be more **non-uniform** so the Breakdown voltage , so the V_{BD} will be less
- gap is still small So no difference between V_{incep} and V_{BD}

Region (3)

- gap is long that the diameter won't affect the operation
- at a certain voltage the $V_{inception}$ of corona happens , but no V_{BD}
- so we need a higher voltage to cause breakdown (that's what happen with overhead T.L)
- that's why we increase distance with the voltage increase we must increase the tower height with increase of voltage
- in high voltages we use **Bundle conductors** (larger diameter) to make the field quite uniform so less corona happens

---

Breakdown in non-uniform field

$$\alpha, \gamma \propto \frac{E}{P} \qquad and \quad E \rightarrow variable$$

$$\therefore \alpha, \gamma \rightarrow is\ variable\ too$$

$$\therefore \boldsymbol{\gamma} \left[\boldsymbol{e}^{\int_0^d \alpha\, dx} - \mathbf{1} \right] = \mathbf{1} \quad \Rightarrow \quad ((Condition\ for\ Breakdown))$$

For problems

- if $given\ \alpha\ (x)\ then\ integer\ \alpha$
- if $given\ \gamma(x) then\ integer\ \gamma\ too$

Breakdown under high voltage AC (f = 50 Hz)

In case of DC of 20kV it's always 20kV so if $V_{BD} = 20kV$ it will break down

But in case of AC of peak 20kV and V_{BD}
- it may not Break down because of the T= 0.02 so it won't have enough time to break down

But if the break down happened in μSec then it may Breakdown

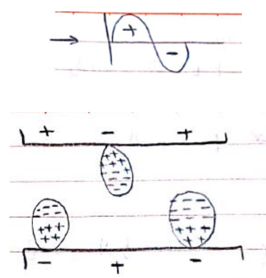
Breakdown under high voltage & High Frequency

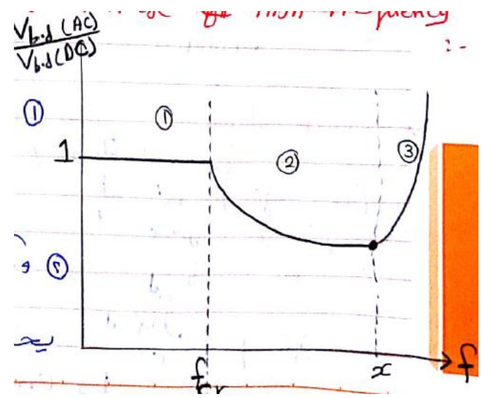
(1)When the frequency increases the same breakdown of DC will happen so $\frac{V_{BD}(AC)}{V_{BD}(DC)} = 1$

(2) But at **Critical Frequency** following happens

BD creates avalanche but the voltage polarity changes so avalanche changes so
<u>+ve charges are cumulated</u> in the gap
so we will need **less V_{BD}**

$$so, \frac{V_{BD}(AC)}{V_{BD}(DC)} < 1$$





Critical frequency (f_{cr}) : the frequency at which all positive ions can just be cleared from the gap during one half-cycle

(3)at point x the increase of frequency makes <u>–ve charges and +ve charges cumulated in the gap</u>

So we will need higher voltage to isolate them

$$so, \frac{V_{BD}(AC)}{V_{BD}(DC)} > 1$$

Breakdown under impulse voltage

Conditions of Breakdown

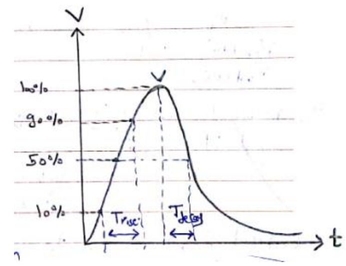
1- initial electrons
2- that electrons has enough energy to ionize the atoms at collision

Impulse Voltage

It's defined by two times

T_{rise} : $for\ impulse\ from$ 10% to 90%
T_{dcay}: $for\ impulse\ from$ 100% to 50%

$T_{rise} \ll T_{decay}$ and they both are very small

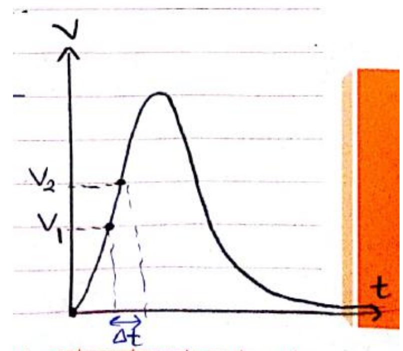


$$1.2/50\ \ \mu Sec$$

$$means : T_{rise} = 1.2\mu Sec\ and\ T_{decay} = 50\ \mu Sec$$

Breakdown under impulse

At imposing an impulse on the gas the breakdown takes time **<u>(Time-lag)</u>**



V_1 : $Breakdown\ required\ Voltage$
V_2: $Voltage\ at\ which\ breakdown\ happened$

Δt : $the\ time\ needed\ for\ voltage\ to\ reach\ V_2$
$(time - lag)$

$$\Delta t = satistical\ time\ lag + formative\ time\ lag$$

$\boldsymbol{satistical\ time\ lag}$: $time\ between\ enough\ voltage\ foor\ BD\ and\ emission\ of$ $\boldsymbol{initial\ electron}$

$\boldsymbol{formative\ time\ lag}$
: $time\ taken\ between\ emission\ of\ electron\ from\ cathode\ and$ $\boldsymbol{formation\ of\ avalanche}$

Note :

(1) Time-lag existis in both DC and AC (low freq)

DC : the voltage is constant at any time

AC(low frequency) : time lag is very small Δt (μSec) then the polarity won't have time to change

(2) For the same gas
$if\ V_{BD}(DC) = 8\ kV\ then\ V_{BD}(impulse\ ) = 10\ kV$

Ch3 : Break Down in Liquid

Liquid Seems good as
1- it fills the place it's put in 2- oil is about 10 times more efficient than air or nitrogen in its heat transfer capability when used in transformers

Types of Oils

1- Organic Oils : vegetable oil + alcohol = esters : contain C-H-O
2- Mineral Oils : paraffins C_nH_{2n+2} (n=10:40)
3- Synthetic Oils : silicon oils : property : non-falmmability
4- Based Nano fluids oils : enhance thermal conduc. And dielectric strength
obtained by : stable suspension and dispersion of low volume fraction of nano particles.

Breakdown Mechanisms

It's more complex than gas and solids ; cuz : 1- no theory on physical basis of liq state 2- impurities and cavities (so we say B.D depends on impurity content more than molecular composition)

1- Electronic Breakdown theory
2- Cavity or bubble theory
3- The suspended particle theory

(1) Electronic Breakdown Theory

Cathode emits electrons , as these electron travel to anode , they collide with atoms to knock off some of their electrons to take them with them in their trip to the anode

This case applys only on : homogenous liquid of extreme purity (not practical)

(2) Cavity or Bubble theory

Formation of gas bubble
a- gas pockets on the electrode surface

b- Changes in temperature and pressure

c- Dissociation of products by electron collision giving rise to gaseous products

d- vaporization of the liquid by corona type discharges from sharp points and irregularities on the electrode surface

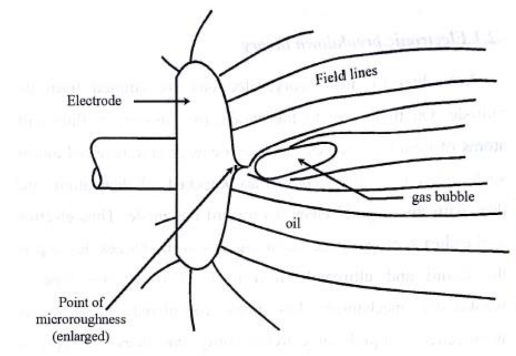


Figure 3.1: Formation of a gas bubble at a point on the electrode surface in an oil gap

-once a bubble is formed it will lengthen under electrostatic force but it's volume remains the same

- electric field inside the bubble is much higher than in liquid

- discharge occurs – when the length is equal paschen's minimum value so breakdown and discharge which causes for vaporization

- vaporization causes more bubbles

so **Breakdown Field is :**

$$E_0 = \frac{1}{\varepsilon_{liq} - \varepsilon_b}\left\{\frac{2\pi\sigma(2\varepsilon_{liq} + \varepsilon_b)}{r}\left[\frac{\pi}{4}\sqrt{\frac{V_b}{2rE_0}} - 1\right]\right\}^{\frac{1}{2}}$$

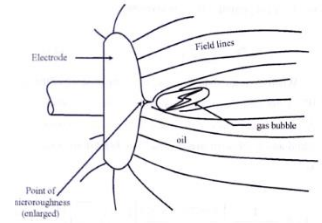


Figure 3.2: Gas discharge in the bubble

And electric field in spherical bubble

$$E_b = \frac{3E_0}{\varepsilon_{liq} + 2}$$

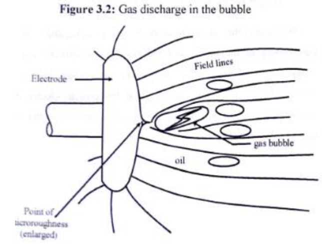


Figure 3.3: Gas discharge in the bubble

Where σ : $surface\ tension$

$\varepsilon_{liq} = \varepsilon_0\varepsilon_r\ also\ \varepsilon_b\ same$

r : $initial\ radius\ of\ bubble$

V_b ; $voltage\ drop\ in\ bubble$

Equation indicate <u>Field Strength required for breakdown of liquid depends upon the initial size of the bubble</u>

Suspended Particle Theory

There maybe solid impurities too : fibres, dispersed solid particles

It will experience force of

$$F_e = \varepsilon_{liq}\, r^3 \frac{\varepsilon - \varepsilon_{liq}}{\varepsilon + 2\varepsilon_{liq}} E * \nabla E$$

$$if\ \varepsilon > \varepsilon_{liq} \rightarrow Force\ acts\ towards\ place\ of\ maximum\ stress$$

$$if\ \varepsilon < \varepsilon_{liq} \rightarrow Force\ acts\ Oppsite$$

$$if\ \varepsilon \rightarrow \infty\ \ F_e = \varepsilon_{liq}\, r^3 E\ \nabla E$$

If field is uniform : it will act toward uniform : remain in **equilibrium**

But if it has permittivity higher than the medium field will concentrate on it's surface attracting other particles causing **<u>head to tail for a bridge</u>** across the gap , then field reaches the critical value and breaks down

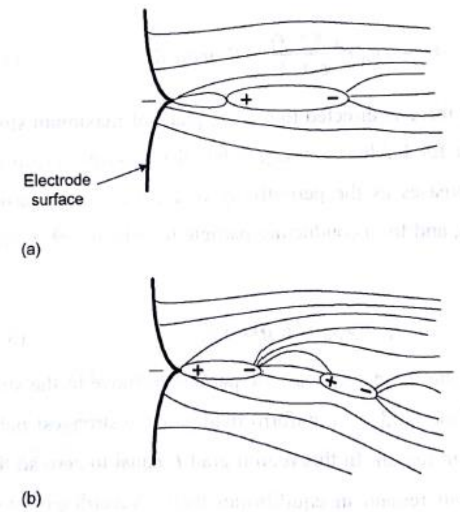


Figure 3.4: Steps of collection of particles in suspension to eventually bridge the oil gap

Stressed Oil Volume Theory

In commercial oils the break down is determined by : "**Largest Possible Impurity"**

So it's indicated by the most stress volume (SOV) <u>taken volume between E_{Max} and $0.9E_{Max}$</u>

<u>The Breakdown strength is inversely proportional to the stressed oil volume</u>

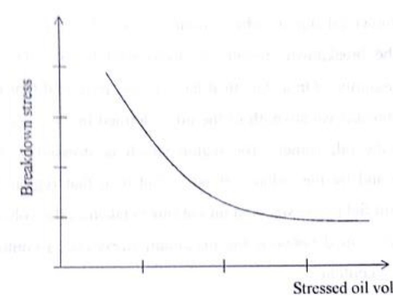


Figure 3.5: Dependence of breakdown stress on stressed oil volume

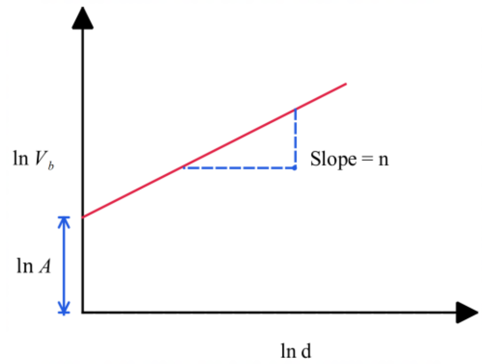
Dependence on gap length

$$V_b = Ad^n \rightarrow \ln V_b = \ln A + n\ \ln d$$

It depends also on:

1- Nature and mode of voltage
2- Time of application

Mechanism of BD in oil is complex and electrical stress on small volume can't be applied on larger volumes



Ch 4 : Breakdown in Solid Dielectrics

We need it for : Mechanical Support , insulate conductors , practical it's a mix solid with gas or liquid

Disadvantage :
- breakdown occurs, solids get permanently damaged while gases and liquids partly recover their dielectric strength after the applied electric field is removed.

- Complex no theory

Reason for complexity : factors Breakdown depend on

1- **Material temperature**
2- **Voltage duration**
3- **Ambient conditions**

Mechanisms

1- **Intrinsic Breakdown**
2- **Electromechanical breakdown**
3- **Treeing**
4- **Tracking**
5- **Thermal breakdown**
6- **Electrochemical breakdown**
7- **Partial discharge breakdown**

1- Intrinsic Breakdown (electronic breakdown)

due to the electronic behavior of the dielectric with no effect of ambient or temp. rise

Description :
possible for idealized crystalline materials. When a field is applied to a crystal, electron would be accelerated by the applied electric field E and ,would collide with some lattice sites on their way. The rate of energy gain by electrons from the field and the rate of energy loss from electrons to lattice vary as shown schematically

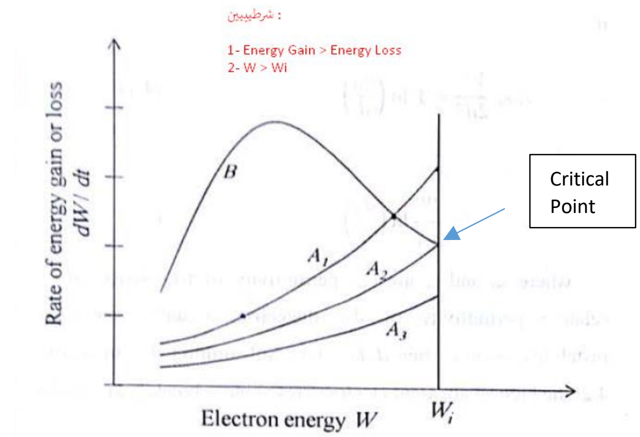


Figure 4.1: Rate of energy gain by electrons from the field and rate of energy loss from electrons to lattice

2- Electromechanical Breakdown

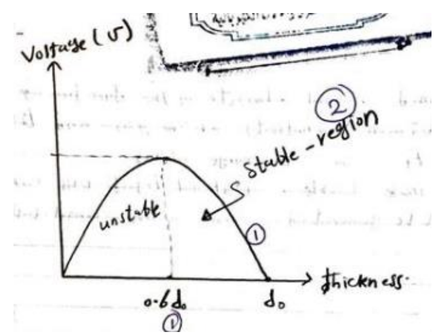
$$electric\ field \rightarrow\ electrostatic\ compressive\ forces$$

$$V^2 = d^2 \frac{2Y}{\varepsilon_0 \varepsilon_r} \ln\left(\frac{d_0}{d}\right)$$

$$Mechanical\ nastability\ happens\ when \frac{d}{d_0} = e^{-\frac{1}{2}} = 0.6$$

$$\therefore\ before\ breakdown\ \ E_{Max} = 0.6\sqrt{\frac{Y}{\varepsilon_0 \varepsilon_r}}$$

This equation ignores the possibility of dependence of y on time and stress.



3-Treeing

In practical there is in molecular structure of polymers some **imperfections as metallic particles, cavities or deteriorated particles of material** even **water** can diffuse through microscopic cracks and sheaths

That cause : initiate **discharge at relatively <u>low applied voltage</u>**
That will disturb the field and transform it to **highly non-uniform**

- **Cause Breakdown at tip then,** extending step by step through the whole thickness in form of **Tree branches (treeing)**

<u>**Time**</u> : several seconds – few minutes

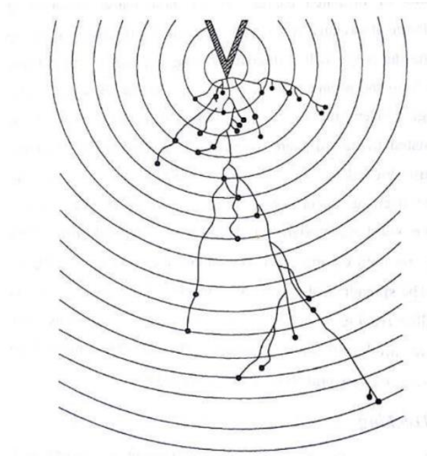


Figure 4.2: Development of breakdown channels in solid dielectrics in a form of a tree (Treeing)

4-Tracking

Tracking is the formation of a permanent conducting path across a surface of insulation.
cause : -degradation of insulation – covering by contaminants such salt and dust – moisture film by(condensation or precipitation,)

Conduct : **Leakage Current** magnitude **(type – extent)** of pollution, **heat** the surface causing interruption in moisture **distorting stress distribution over the surface**

(Dry-bands) will form (high resistivity in wet film **Nearly the total surface voltage will appear across this dry-band ->** causing <u>**flashover**</u> of the gap , arc continue until gap widen arc can't maintain

<u>**For organic material :**</u> the temp. of arc will decompose **carbon** it limit it's use <u>outdoor</u>

<u>**All this cause :**</u> will proceed in a relatively random manner until a continuous conducting path

forms between the live parts or at least bridges a sufficient portion of the surface, resulting in <u>**flashover**</u>

Tracking has a ch/c <u>branched</u> appearance

5-Thermal Breakdown

Breakdown voltage increase with thickness to certain level where <u>**heat** from flow of current</u> will determine the breakdown

Thermal breakdown when $heat\ generated > heat\ dissipated$

When **Electric field** applied -> **conduction current** flows ,**heats the specimen** and transferred (conduction – radiation)

HEAT GENERATED

$$W_{DC} = E^2\sigma$$

$$W_{AC} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \quad W/cm^3$$

HEAT DISSIPATED

$$W_T = C_v \frac{dT}{dt} + \overline{\nabla}\,(K\,\nabla T)$$

Equilibrium when ($W_{DC} or W_{AC} = W_T$)

Breakdown when ($W_{DC} or W_{AC} > W_T$)

6-Electrochemical Breakdown

Oxidation: In the presence of air or oxygen, materials such as rubber and polyethylene undergo oxidation **giving rise to surface cracks.**

Hydrolysis: When moisture or water vapor is present on the - surface of a solid dielectric, hydrolysis occurs and the materials **lose · their electrical and mechanical properties,**
- paper and other cellulose materials deteriorate very rapidly due to hydrolysis

-plastic like polyethylene undergo changes, and their service life considerably reduces.

Chemical Action: Even in the absence of electric fields, **progressive chemical degradation** of insulating materials can occur due to a variety of processes.

-Chemical reactions occurring in dielectric materials lead to reduction in electrical and mechanical strengths resulting in failure.

7-Partial Discharge breakdown

Practical solid insulators has cavities , that has **lower** breakdown strength & **High** field intensity

So during normal operation Voltage in cavity may exceed the breakdown that called **partial discharge**

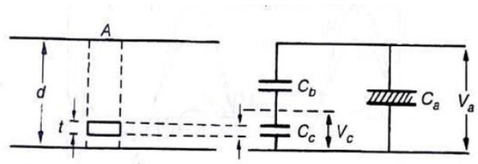


Figure 4.3: Electrical discharge in a cavity and its equivalent circuit

$$V_c = \frac{V_a t}{t + \frac{(d-t)}{\varepsilon}}$$

$$if\ V_a\ is\ that\ \ V_c > V_i\ \ (\ cavity\ will\ \boldsymbol{breakdown})$$

If voltage is AC breakdown will happen on both sides of the half cycle

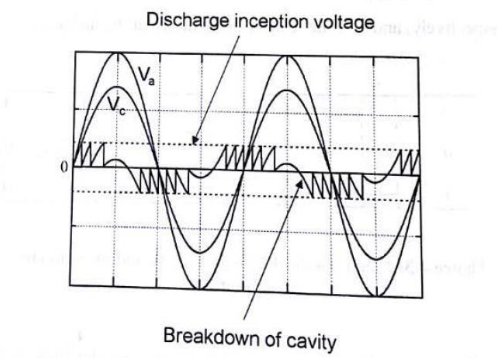


Figure 4.4: Sequence of cavity breakdown under alternating voltages

If sparks around zero – void but If sparks around peak - metalic impurity

V incp and V extinction إنطفاء $in\ no\ of\ discharges\ in\ quarter = \frac{V_c}{V_i - V_e}\quad then \times 4\ \ in\ cycle$

Treeing : Partial discharge will have <u>the same effect as treeing on the insulation</u>

Chemical : electrons and positive ions are formed. They will have sufficient energy and when they reach the cavity surfaces they may break the chemical bonds

Thermal : discharge there will be some heat dissipated in the cavity

- this will carbonize the surface of the cavity and will cause erosion of the material
- Channels and pits formed on the cavity surfaces increase the conduction
- Chemical degradation as result of active discharge products during break down

This cause :

- gradual erosion of the material and consequent reduction in the thickness of insulation leading to breakdown.
- The life of the insulation with partial discharges depends upon the **applied voltage** and the **number of discharges**.
- Breakdown by this process may occur in a few days or may take a few years.

Generation of high AC voltages

- Most test is made at HV (to simulate the system effects on insulation)

Single transformer : generate HV up to <u>few hundred kV</u>
For higher than that it will face some problems :

1- Insulation Problems
2- Expenses
3- Transportation
4- Construction problems

Cascaded Transformers

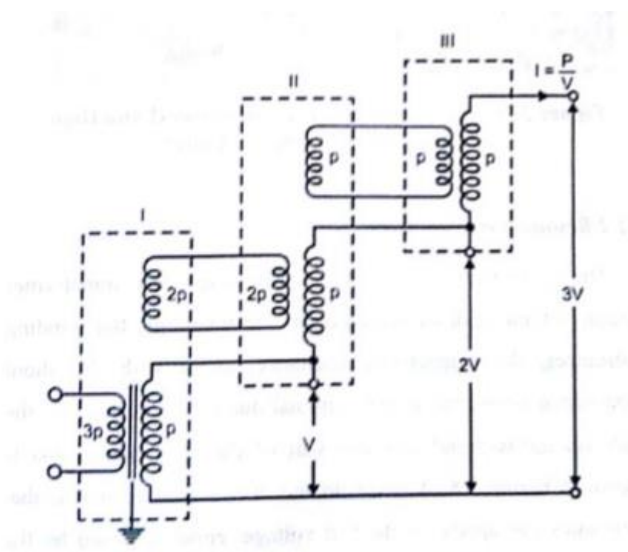


Figure 5.6: Cascaded transformer for generation high AC voltages

- Every low voltage winding is excited from the stage immediately below it
- Both windings are rated at current **higher** than those of the high voltage winding
- The excitation at lower stages **carry higher loading** than those upper stages
- The total short circuit impedance of a cascaded transformer can be from data of one stage
- If the output of first stage then **output voltage = V*no.of.stages**
- Except for the first stage, the iron core and container are insulated from earth because their voltage doesn't start from 0 but from a value (**which is expensive)**

To reduce the size and cost of insulation :

We use **transformers with centre-tapped high-voltage winding so**

First stage tank at V/2 , second at 3V/2, third at 5V/2

Resonant Transformer

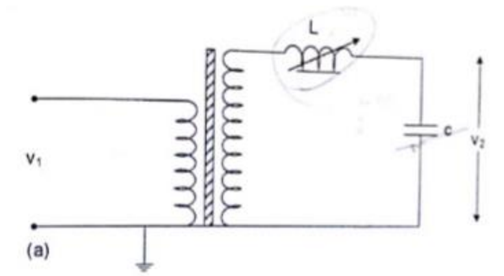
The equiv. Circuit of single-stage test transformer consist of $X_{leakage}$, $R_{winding}$

X_m *and* X_c *are shunt at output terminals*

<u>Disadvantage :</u>

Harmonics can appear in the test voltage (from supply or generated in transformer(nonlinearity))

Because of these harmonics simple straight test circuits won't be suitable for certain tests.



gure 5.8: Simplified circuit of a testing transformer with added reactor L

<u>Solution</u> (Moore Economic , Technically superior) is RESONANT TRANSFORMER

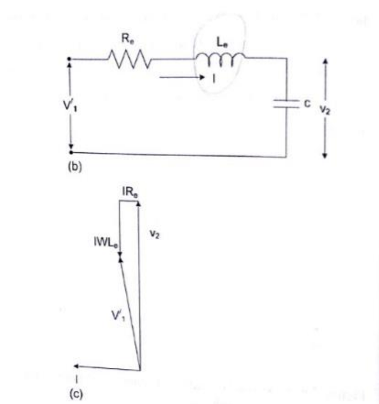


Figure 5.9: Equivalent circuit together with the phasor diagram for a resonant transformer

Achieveing Resonance in the circuit through adding a series reacor L at test frequency so,

- Harmonics heavily attenuated.
-The current in test object is very large and is only limited only by circuit resistance

- Series resonance sets are usually brought into resonance by mechanical adjustment of an air gap in the iron core of the reactor

$$V_C = \left|\frac{-jV'_2\,X_C}{R + j(X_L - X_C)}\right| = \frac{V'_2 X_C}{R} = \frac{V'_2}{\omega CR}$$

$$Q\,factor = \frac{X_C}{R} = \frac{1}{\omega CR}\ \ (magnitude\ of\ voltage\ multiplication\ across\ test\ object)$$

$$input\ voltage\ required\ reduced\ by\ a\ factor\ of\ \frac{1}{Q}$$

$$output\ kVA\ required\ is\ also\ reduced\ by\ a\ factor\frac{1}{Q}$$

We use this principle at

1- Testing very high voltages
2- Under requirements of large current output such as <u>cable testing</u>

Advantages :

1- Pure sinsuidal output waveforms.
2- Less power requirements from the mains
3- No high power arcing or heavy current surges occur if the test object fails, as the resonance is heavily disturbed by the resulting short circuit.
4- Cascading is also possible for producing very high voltages
5- Simple and compact test setup

Disadvantage :

1- Additional variable reactors should withstand the full-test voltage and full-current rating.

Generation of High DC voltages

Commen ways (1- High AC then rectifier ; 2- Van de Graaff)

It has ripple $\propto$ with load current

Amplitude of ripple $\delta V = 0.5\ (V_{Max} - V_{Min})$

For needed small ripple <u>high frequency</u> is better than power frequency in AC, so we won't need expensive filters to suppress the ripple

Half-wave and full wave rectifier circuits

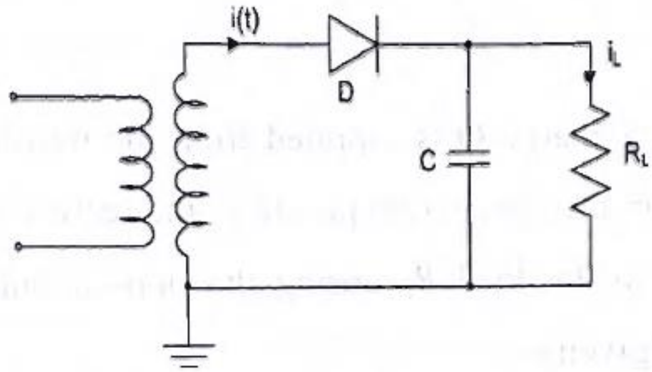
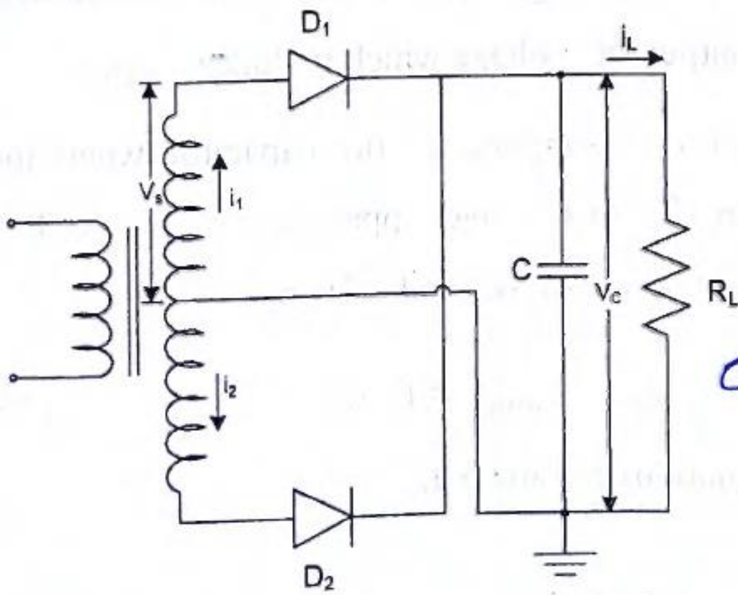


Figure 5.1: Half-wave rectifier for generation of high DC voltages



Center_tapped.

Figure 5.2: Full-wave rectifier for generation of high DC voltages

R_L : *Load*

C : *Smoothing Capacitance*, (*removes pulsation*)

D : *diode must be rated at* $2V_{max}$

δV *is larger for half wave than full wave because discharge period is larger*

Analysis

$$\int_T i_L(t)dt \ = \int_T \frac{V_c(t)}{R_L}\ dt = IT = \frac{I}{f}$$

$$Voltage\ changes\ from\ V_{Max} to\ V_{Min}$$

$$I\ :\ avertage\ DC\ current\ , V_c(t)\ output\ DC\ woth\ ripple$$

$$Q = C(V_{Max} - V_{Min}) = C * 2 * \delta V = \frac{I}{f}$$

$$\therefore C\ 2\delta V\ = \frac{I}{f}$$

$$\therefore\ \ \delta V\ = \frac{1}{2fC}$$

$$f\ :\ ripple\ frequency\ (\ HW\ := supply\ frequency\ \&\ FW\ := 2 * supply\ f)$$

Ripple in rectifier output depend on

1- Load current
2- Circuit parameters (f , C) $\therefore$
   $the\ product\ \boldsymbol{fC\ is\ an\ important\ DESIGN\ FACTOR\ for\ rectifiers}$
3- The higher frequency and larger smoothing capacitor the DC will have less ripple

Voltage Doubler

Rectifiers -> DC with AC max voltage

When higher is needed we use voltage doubler

In voltage doubler circuit and during the negative half cycle the capacitor C_1 is charged through rectifier D_1 to a voltage of $+V_{max}$ with polarity as shown in the figure. As the voltage of the transformer rises to positive V_{max} during the next half cycle, the potential of the other terminal of C_1 rises to a voltage of $+2V_{max}$. Thus, the condenser C_2 in turn is charged through D_2 to $+2V_{max}$.

Normally the DC output voltage on load will be less than $+2V_{Max}$ depending on the **time constant** of the circuit

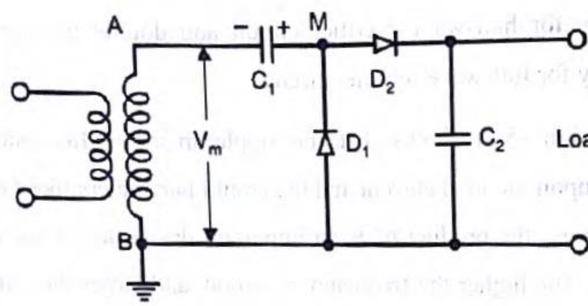


Figure 5.3: Voltage doubler circuit

Voltage Multiplier circuit (Cockcroft-Walton)

Repetition of voltage doubler with cascaded connection

$$total\ output : 2nV_{Max}$$

But voltage across any individual capacitor or rectifier is $2V_{Max}$

Except C_1 charged to V_{Max}only

Actually , when loaded it doesn't reach $2nV_{Max}$ $because\ of$ $1 - \delta V$ $2 - \Delta V$

$$\boldsymbol{\delta V = \frac{1}{fC}\frac{n(n+1)}{2}}$$

$$\boldsymbol{percent\ ripple = \frac{\delta V}{2nV_{Max}}}$$

$$\boldsymbol{\Delta V = \frac{I}{fC}\left[\frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6}\right]}$$

$$\boldsymbol{Reg\% = \frac{\Delta V}{2nV_{Max}}}$$

$$\boldsymbol{to\ achieve\ highest\ output\ voltage\ for\ same\ I, V_m, f, C}$$

$$\boldsymbol{n_{opt} = \sqrt{\frac{(V_{Max} f C)}{I}}}$$

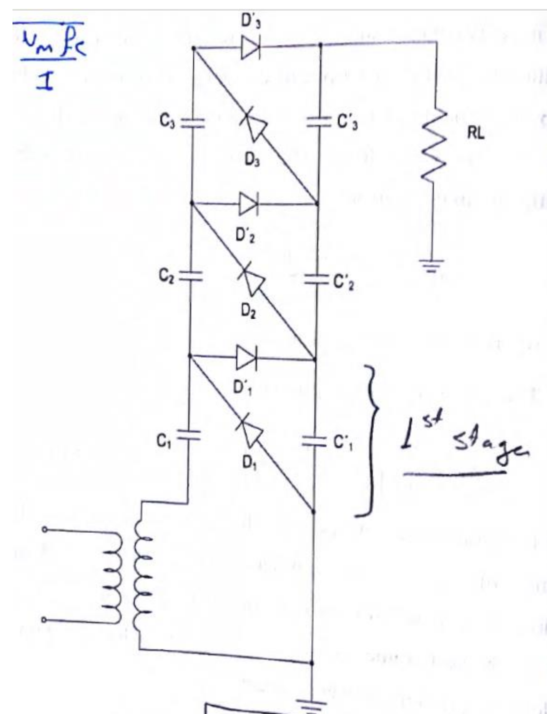


Figure 5.4: Voltage multiplier circuit

Electrostatic Generators

Electromagnetic machine	Electrostatic Machines
current carrying conductors are moved in a magnetic field, so that the mechanical energy is converted into electrical energy	Charged bodies are moved in an electric field against an electrostatic field in order that mechanical energy is converted into electrical energy

Van de Graaff generator (electrostatic machine) generates very high DC , used in <u>nuclear physics reseach laboratories</u>

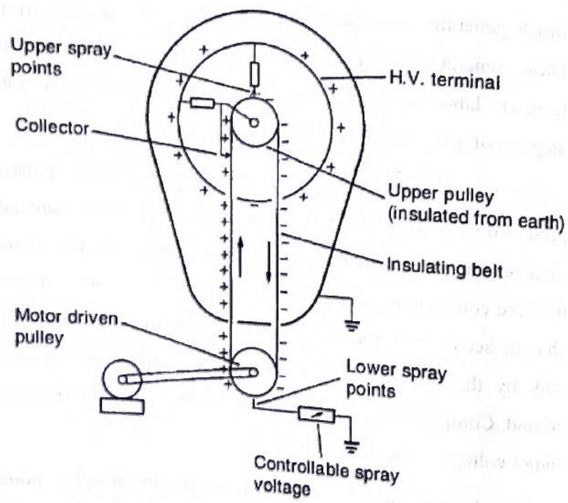


Figure 5.5: Schematic diagram of a Van de Graaff generator

1- the ions of positive polarity produced by corona at pointed electrodes are carried mechanically by a very highly insulating belt to the top of the apparatus
2- where they are conducted to a high-voltage terminal
3- As more and more charges accumulate, the generator voltage builds up. It is limited only by the dielectric strength of the terminal' s insulation to ground
4- Compressed gas and/or grading rings are used to raise the output voltage of the generator.
5- The charging of the belt is done by the lower spray points which are sharp needles and connected to a DC source of about 10 to I 00 kV, so that the corona is maintained between the moving belt and the needles.
6- The charge from the corona point is collected by the collecting needles from the belt and is transferred on to the high voltage electrode as the belt entres into high voltage electrode. The belt returns with the charge dropped, and fresh charge is sprayed on to it as it passes through the lower corona point

<u>Self-charging system</u>

1- in order to make the charging more effective and to utilize the return path of the belt for charging purposes

2- self inducing arrangement is commonly used for spraying on the down-going belt charges of polarity opposite to that of the HV terminal.
3- The **rate of charging of the terminal**, for a given speed of the belt. is therefore **doubled.**

To obtain a self-charging system

1- the upper pulley is connected to the collector needle and is therefore maintained at a potential higher than that of the HV terminal.
2- The device includes another system of points which is connected to the inside of the HV terminal and is directed towards the pulley at the position shown.
3- As the pulley is at a higher positive potential. the negative charges of the corona at the upper spray points are collected by the belt.
4- This neutralizes any remaining positive charges on the belt and leaves any excess negative charges which travel down with it and are neutralized at the lower spray points.

Advantages

1- the high output DC voltages which can easily be reached,
2- the lack of any fundamental ripple
3- the precision and· flexibility

Disadvantaged

1- the limited current output
2- the tendency of belt for vibrations causing problems regarding accurate grading of the electrical fields
3- The maintenance necessary due to the mechanically stressed parts.

Generation of High Impulse voltages

An impulse voltage is a unidirectional voltage which rises rapidly to a maximum value and falls more or less rapidly to zero

(as in the case of transient overvoltages due to lightning or switching surges.)

Standard impulse $e\ (t) = A[e^{-\alpha_1 t} - e^{-\alpha_2 t}]$

Front Time , Rise Time : time taken by the wave to reach to its maximum value starting from zero value.

But,easier : = **1.25 $\times$ time from 10% to 90% of peak**

Tail Time , Fall Time : is measured between the nominal starting point and the point on the wave tail where the voltage is 50% of the peak value

Ex : 1.2/50μs, 1000kV : rise time 1.2 μS and fall 50 μS max value f V = 1000kV

Lightining and switching Rise : 0.5 : 10 μs and tail : 30 : 200 μs

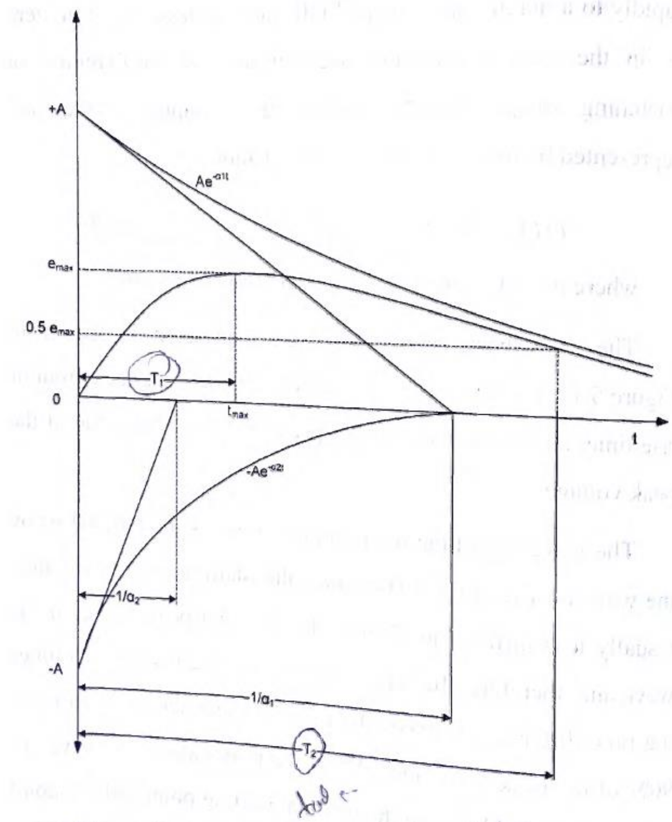


Figure 5.11: Impulse waveshape and its parameters

Impulse voltage generator circuit

Can be made of one RLC circuit or two RC circuits

Number (b) and (c) are most common : Because

1- we can independently control rise and fall time through R_1, R_2
2- Test object represent part of C_2

The capacitor C 1 is charged from a DC source to the desired value which forms the initial magnitude V. On breakdown of the spark gap G the capacitor C1 discharges through the circuit while its voltage decreases fron1 its initial magnitude

R_1 : *Damp the circuit so controls the* ***front time***

R_2 : *discharge the capacitors so controls* ***wave tail***

C_2 : *represents test object and part of other capacitances in parallel*

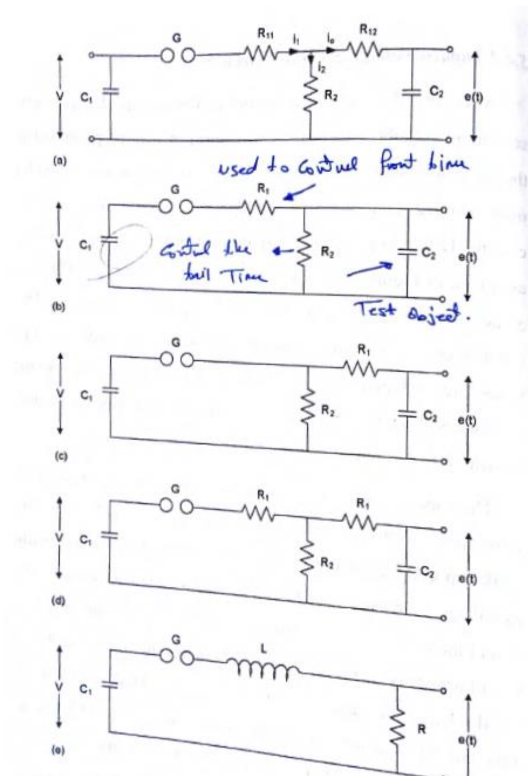


Figure 5.12: Circuits for producing impulse voltage waves

- Peak value can't exceed $e_{Max} < \frac{C_1}{C_1+C_2} V$

$$\eta = \frac{e_{Max}}{V} < \frac{C_1}{C_1 + C_2}$$

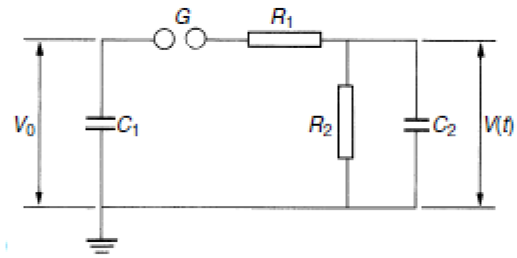
$$so\ for\ better\ efficiency\ C_1 \gg C_2$$

most significant parameter of the impulse generators is the **maximum stored energy**

$$W = \frac{1}{2} C_1 V_{Max}^2$$

$$so\ it\ determines\ cost\ of\ impulse\ generator\ (C_1)\ \ cuz\ C_1 > C_2$$

$$in\ this\ we\ will\ analyse\ \ (b)$$



$$e(t) = \frac{1}{C_2}\int_0^t i_0(t)\,dt$$

where i_0 is the current through C_2.

Performing Laplace transformation

$$E(s) = \frac{1}{C_2 s} I_0(s) \tag{5.13}$$

Taking the current through C_1 as i_1 and its transformed value as $I_1(s)$, then:

$$I_0(s) = \left[\frac{R_2}{R_2 + \frac{1}{C_2 s}}\right] I_1(s) \tag{5.14}$$

In terms of the initial charging voltage V, $I_1(s)$ is given by:

$$I_1(s) = \frac{V}{s} \frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}} \tag{5.15}$$

Substitution of $I_1(s)$ gives:

$$E(s) = \frac{1}{C_2 s} \frac{R_2}{R_2 + \frac{1}{C_2 s}} \frac{V}{s} \frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}} \tag{5.16}$$

After simplification and rearrangement:

$$E(s) = \frac{V}{R_1 C_2}\left[\frac{1}{s^2 + \left(\frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} + \frac{1}{C_2 R_1}\right) s + \frac{1}{C_1 C_2 R_1 R_2}}\right] \tag{5.17}$$

Or

$$E(s) = \frac{V}{R_1 C_2}\left[\frac{1}{s^2 + As + B}\right] \tag{5.18}$$

where the constants A and B are given as follows:

$$A = \left(\frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} + \frac{1}{C_2 R_1}\right) \tag{5.19}$$

$$B = \frac{1}{C_1 C_2 R_1 R_2} \tag{5.20}$$

$E(s)$ can be expressed as follows:

$$E(s) = \frac{V}{R_1 C_2}\left[\frac{1}{(s+\alpha)(s+\beta)}\right] \tag{5.21}$$

α and β are the roots of the equation $s^2 + As + B = 0$. Then they are given as follows:

$$\alpha = \frac{A}{2} - \sqrt{\left(\frac{A}{2}\right)^2 - B} \tag{5.22}$$

$$\beta = \frac{A}{2} + \sqrt{\left(\frac{A}{2}\right)^2 - B} \tag{5.23}$$

Thus the partial fraction expansion of $E(s)$ takes the form:

$$E(s) = \frac{V}{R_1 C_2(\beta - \alpha)}\left[\frac{1}{(s+\alpha)} - \frac{1}{(s+\beta)}\right] \quad (5.24)$$

Taking the inverse transform of $E(s)$ gives:

Taking inverse transform

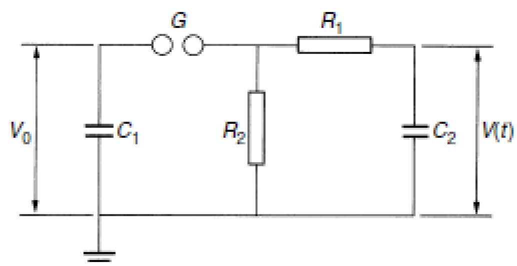
$$e(t) = \frac{V}{R_1 C_2(\beta - \alpha)}\left[e^{-\alpha t} - e^{-\beta t}\right]$$

- is therefore the superposition of two exponential functions of different signs
- the negative root leads to a larger time constant
- $\frac{1}{\alpha}$ than the positive one, which is $\frac{1}{\beta}$.

OTHER CIRCUITS

---

(1)



$$E(s) = I_0(S) * \frac{1}{C_2 S} \rightarrow (1)$$

$$\because I_0(S) = I_1(S) * \frac{R_2}{R_2 + \left(\frac{1}{C_2 S}\right) + R_1} \rightarrow (2)$$

$$\because I_1(S) = \frac{V}{S} * \frac{1}{\frac{1}{C_1 S} + \frac{\left(R_1 + \frac{1}{C_2 S}\right) R_2}{R_1 + R_2 + \frac{1}{C_2 S}}} \rightarrow (3)$$

Subs from 3,2 to 1

$$\therefore E(S) = \frac{1}{C_2 S} * \frac{R_1}{R_2 + \frac{1}{C_2 S} + R_1} * \frac{V}{S} * \frac{1}{\frac{1}{C_1 S} + \frac{\left(R_2 * \frac{1}{C_2 S}\right) R_1}{R_1 + R_2 + \frac{1}{C_2 S}}}$$

$$= \frac{V}{C_2 S^2} + \frac{R_1}{\frac{R_2 + \frac{1}{C_2 S} + R_1}{C_1 S} + \left(R_2 + \frac{1}{C_1 S}\right) R_1}$$

$$= \frac{V}{C_2} * \frac{R_1}{\left[\frac{R_1 + R_2}{C_1} + \frac{R_1}{C_2}\right] S + (R_1 R_2) S^2 + \frac{1}{C_1 C_2}} \qquad divide \frac{R_1 R_2}{R_1 R_2}$$

$$= \frac{V}{C_2 R_2} * \frac{1}{S^2 + \left[\frac{1}{C_1 R_2} + \frac{1}{C_1 R_1} + \frac{1}{C_2 R_2}\right] S + \frac{1}{C_1 C_2 R_1 R_2}}$$

$$= \frac{V}{C_2 R_2} * \frac{1}{S^2 + As + B}$$

$where$

$$A = \frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} + \frac{1}{C_2 R_1}$$

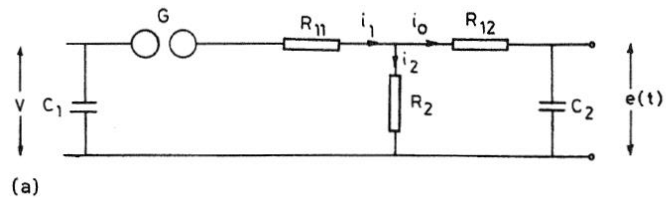
$$B = \frac{1}{C_1 C_2 R_1 R_2}$$

$$\therefore \quad E(s) = \frac{V}{C_2 R_1} * \frac{1}{\beta - \alpha} * \left[\frac{1}{S + \alpha} - \frac{1}{S + \beta}\right]$$

$$where \ \ \alpha = \frac{A}{2} - \sqrt{\left(\frac{A}{2}\right)^2 - B}$$

$$\beta = \frac{A}{2} + \sqrt{\left(\frac{A}{2}\right)^2 - B}$$

$$e(t) = \frac{V}{C_2 R_1 (\beta - \alpha)} * \left[\, e^{-\alpha t} - e^{-\beta t} \,\right]$$



$$E(S) = I_0(S) * \frac{1}{C_2 S}$$

$$\because I_0\,(S) = I_1(S) * \frac{R_2}{R_2 + R_{12} * \frac{1}{C_2 S}} \rightarrow (2)$$

$$\because I_1(S) = \frac{V}{S} * \frac{1}{\frac{1}{C_1 S} + R_{11} + \frac{\left(R_{12} + \frac{1}{C_2 S}\right) R_2}{R_2 * \left(\frac{1}{C_1 S} + R_{12}\right)}}$$

$$subs\ from\ 3{,}2\ to\ 1$$

$$\therefore \boldsymbol{E(S) = \frac{1}{C_2 S} * \frac{R_2}{R_2 + R_{12} * \frac{1}{C_2 S}} * \frac{V}{S} * \frac{1}{\frac{1}{C_1 S} + R_{11} + \frac{\left(R_{12} + \frac{1}{C_2 S}\right) R_2}{R_2 * \left(\frac{1}{C_1 S} + R_{12}\right)}}}$$

$$= \frac{V}{C_2 S^2} * \frac{R_2}{[R_1(R_1 + R_2) + R_1 R_2] + \left[\left(\frac{R_1 + R_2}{C_1 S}\right)\left(\frac{R_1}{C_1 S}\right)\left(\frac{R_1}{C_2 S}\right)\right]}$$

$$= \frac{V}{C_2} * \frac{R_2}{S^2 * [R_1(R_1 + 2R_2)] + \left[\frac{R_1}{C_1} * \frac{R_2}{C_2} + \frac{R_1}{C_2} + \frac{R_2}{C_1}\right] * \frac{1}{C_1 C_2}}$$

$$= \frac{V}{C_2 * \frac{R_1}{R_2}[R_1 + 2R_2]} * \frac{1}{s^2 + As + B}$$

$$where\ \ A = \frac{\left(\frac{R_1}{C_1} + \frac{R_2}{C_2} + \frac{R_1}{C_2} + \frac{R_2}{C_1}\right)}{R_1(R_1 + 2R_2)}$$

$$B = \frac{1}{C_1 C_2 R_1 (R_1 + 2R_2)}$$

$$then \quad e(t) = \frac{V}{C_2 * \frac{R_1}{R_2}[R_1 + 2R_2](\beta - \alpha)} \left[e^{-\alpha t} - e^{-\beta t} \right]$$

$$where\ \alpha = \frac{A}{2} - \sqrt{\left(\frac{A}{2}\right)^2 - B} \quad \beta = \frac{A}{2} + \sqrt{\left(\frac{A}{2}\right)^2 - B}$$

Waveshape control

Generally, for circuits (b) and (c)

C_1, C_2 will be fixed depending on the design of the generator and test object

So we control waveshape through R_1, R_2

The resistance R2 will be large and can be neglected during charging. Then, C_1 charges the load capacitance C_2 through R_1

Time for charging is approx.. **three times the time constant of circuit**

$$\boldsymbol{T_1 = 3\, R_1 \frac{C_1 C_2}{C_1 + C_2}}$$

For multistage :

$$\boldsymbol{T_1 = 3\, R_1 \frac{\frac{C_1'}{n} C_2}{\frac{C_1'}{n} + C_2}}$$

$$R : \Omega \ , C : \mu F \ , \quad T_1 \ : \mu s$$

For discharging or tail time, the capacitances $C_!$and C_2may be considered to be in parallel and discharging occurs through R_1 and R_2

So time for 50% discharge is given by

$$\boldsymbol{T_2 = 0.7\,(R_1 + R_2)(C_1 + C_2)}$$

Multistage impulse generator (MARX)

One C_1 can be used to voltages up to **200kV**

More than 200kV we will need a capacitor (large and costly) as $cost \propto V^2 \; or \; V^3$

MARX why not ?

a number of condensers are charged in parallel through high ohmic resistances and then discharged in series

through spark gaps. N owa days., there are many arrangements, in addition to the arrangement proposed by Marx, for charging the capacitors m parallel and then connecting them in series for discharging.

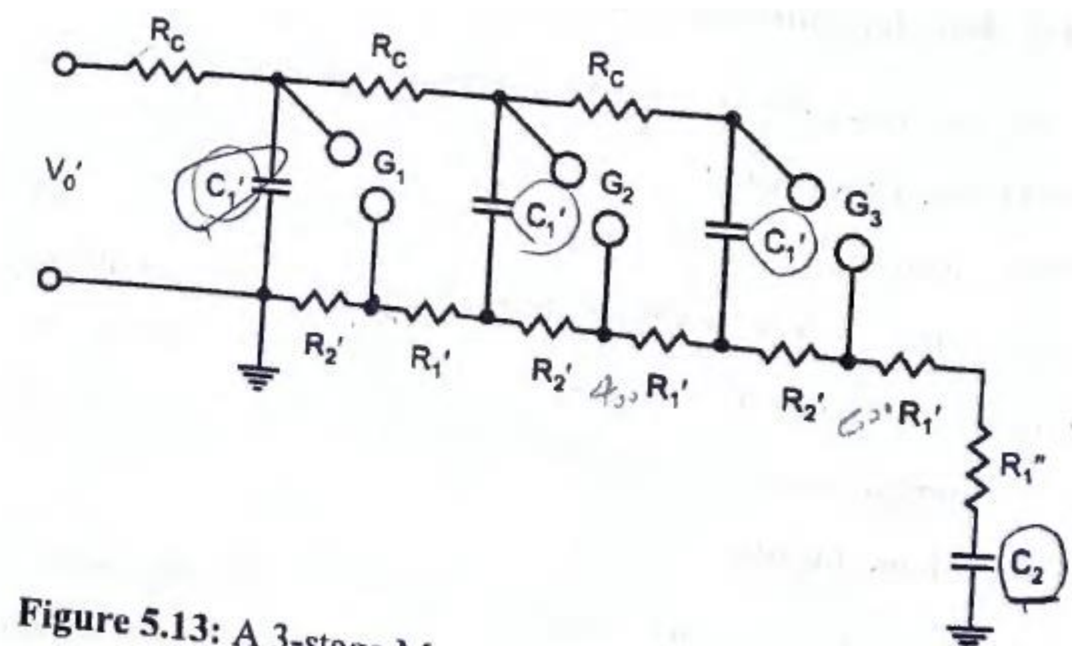


Figure 5.13: A 3-stage Marx impulse generator based on the circuit connection in Figure 5.11b

Operation :

The DC voltage charges the equal stage capacitors C C_1' in parallel through the high value charging resistors R_c . When all gaps G goes into breakdown, the C_1' capacitances are connected in series so that C_2 is charged through the series connection of all the wave front R_1'sistances Rl and finally, all C_1' and C_2 will discharge through the resistors R_2' and R_1'.

To operate consistently : first gap G1 is slightly less than G2 and so on

Reduction to single-stage impulse

$$\frac{1}{C_1} = \sum^{n} \frac{1}{C_1'} \rightarrow C_1 = \frac{C_1'}{n}$$

$$R_1 = \sum^{n} R_1' + R_1''$$

$$R_2 = \sum^{n} R_2'$$

Ch6 : Measurement of High Voltages

High Voltage Measurement Problems

1- that the high voltage equipment have large stray capacitances with respect to the grounded structures
2- protection required for the person handling the equipments and the measuring devices
3- large structures are required to control the electrical fields and to avoid flash over between the equipn1ent and the grounded structures.

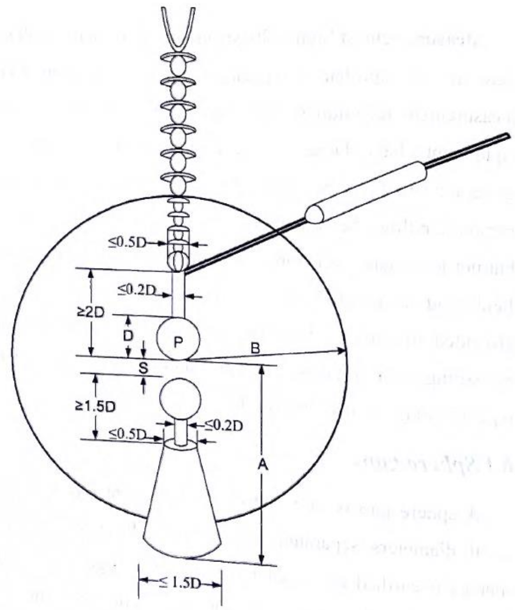
Methods for measuring high voltages

Sphere gaps

- A sphere gap is formed from two adjacent metal spheres of equal diameters separated by a limited distance.
- One : Earthed
- The other : connected to high voltage
- Standard arrangements : Horizontal & Vertical

- The horizontal sphere gap arrangement is preferred at lower measured voltages

Procedure :



establish a **relation** between the **peak voltage**, determined by sparkover between the spheres, and the **reading of a voltmeter on the input side** of the high voltage source

-The results are reliable to within ±3%.

IMPULSE

- The voltage to be measured is aplied between the two spheres and the distance or spacing ~ between them gives a measure of the sparkover voltage using tables relating sphere gap spacing with peak voltage

- Usually a series resistance is connected between the source and the sphere gap in order to limit the breakdown current and to suppress unwanted oscillations in the source voltage when breakdown occurs (in case of impulse voltages).

- Under impulse voltages, the voltage at which there is a 50% breakdown probability is recognized as the breakdown level.

AC & DC

- the applied voltage is uniformly increased until sparkover occurs in the gap. Generally, a mean of about ten breakdown values is taken.

Change in air density

Standard : $T = 20\,°C$; $P = 760\ mmHg$

$$\delta = \frac{P}{760}\left(\frac{293}{273+T}\right)$$

To get K (correction factor)

δ	0.70	0.75	0.8	0.85	0.9	0.95	1	1.05	1.1
k	0.72	0.77	0.82	0.86	0.91	0.95	1	1.05	1.09

$$\boldsymbol{V_s = kV_n}$$

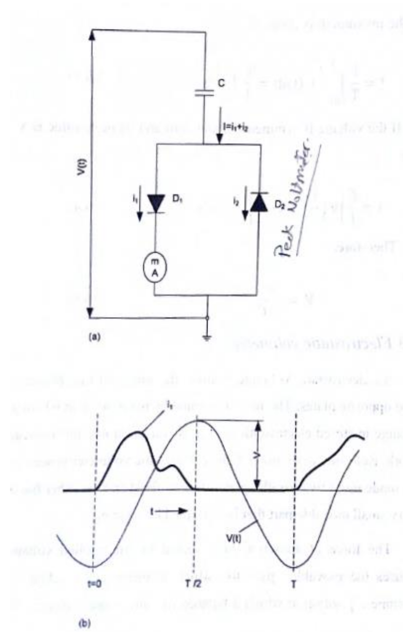
Humidity neglected won't exceed 2% or 3% over normal humidity range

Other Factors

- Nearby Earthed Objects
- Irradiation
- Voltage polarity

Peak Voltmeter

The measuring circuit of a peak voltmeter is shown in Figure and is made up of two diodes, a properly chosen capacitor, and a milliammeter.



$$I = \frac{1}{T}\int_0^{\frac{T}{2}} i_1(t)dt = \frac{C}{T}\int_{-V_m}^{+V_m} dv$$

If voltage is symmetric around zero , it’s peak is V then

$$I = \frac{C}{T}\left[V\left(\frac{T}{2}\right) - V(0)\right] = 2fCV$$

$$\therefore V = \frac{I}{2fC}$$

Electrostatic Voltmeter

Definition

an electrostatic voltmeter utilizes the force existing between two opposite plates. The force is created by the process in which a change in stored electrostatic energy is converted into mechanical work.

Construction

Made up of two plates : one is fixed , the other has a very small movable part that is restrained by a spring.

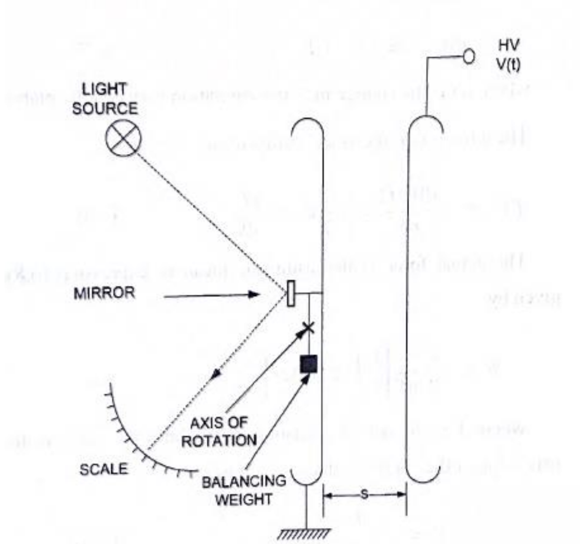


Figure 6.3: Electrostatic voltmeter

Mirror attached to the movable part , incident light beam is reflected toward a scale calibrated to read the applied voltage magnitude

Relations

Assume capacitance between plates C stored electrostatic energy W

$$W = \frac{1}{2} C V^2(t)$$

A change $dW(t) \rightarrow mechanical\ work$

$$dW(t) = -F(t) dS$$

$$F\ (t) = -\frac{dW(t)}{dS} = \frac{1}{2} V^2(t) \frac{dC}{dS}$$

$$\bar{F} = -\frac{1}{2}\frac{dC}{dS}\left[\frac{1}{T}\int_0^T V^2(t)dt\right]$$

$$\bar{F} = -\frac{1}{2}\frac{dC}{dS} V^2$$

$$\because C = \frac{A\varepsilon_0}{S}$$

$$\therefore \boldsymbol{\bar{F} = \frac{A\varepsilon_0}{2S^2} V^2}$$

$$factor\ \frac{A\varepsilon_0}{S^2}\ \ is\ used\ to\ control\ the\ range\ of\ measurment$$

Ammeter in series with a high impedance

An impedance can be used in series with a microammeter or a milliammeter for the measurement of high voltages

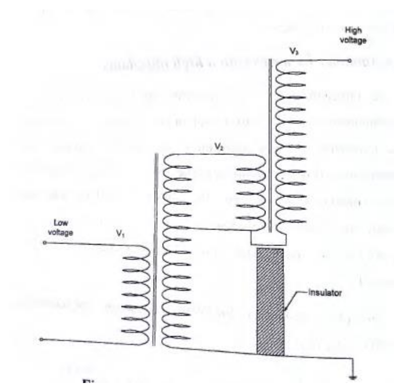
replaced by an oscilloscope if the voltage waveform is to be recorded.

$$V = RI$$

Disadvantage : Stability of the resistance R

Voltage Transformer

The voltage on the secondary side is closely proportional in amplitude to the voltage on the primary side. For very high voltages, cascaded voltage transformers are used as shown

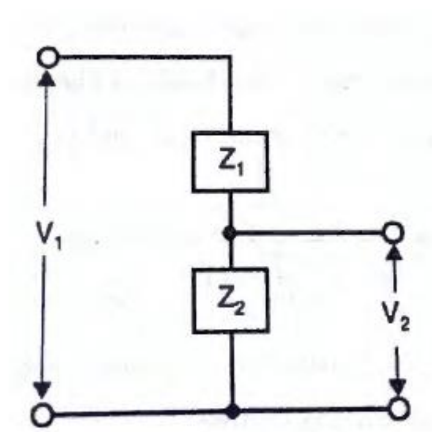


Potential dividers

-Consists of : Resistors , Capacitors or combinations

-Inductors not used **because** pure inductances of proper magnitudes without stray capacitance cannot be built.

$$V_2 = \frac{Z_2}{Z_1 + Z_2} V_1$$



Resistive Potential Divider

To measure **DC high voltages**

Attenuation factor $a = \frac{V_1}{V_2} = 1 + \frac{R_1}{R_2}$

In measuring **AC High voltage or impulse** (**DISADVANTAGES)**

(1)
resistive potential dividers suffer from the disadvantage of **stray capacitances**

These stray capacitances include 3 kinds of capacitances :

1- parallel capacitances between neighboring resistor elements
2- stray capacitances to the HV electrode
3- stray capacitances to earth potential

(2)

The divider element R2, in practice, is connected through the coaxial cable to the oscilloscope. The input impedance of measuring arrangement (the cable and the oscilloscope) C_m

<u>Attenuation or voltage ratio in frequency domain</u> will be

$$a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{R_1}{\left(\frac{R_2 \times \frac{-j}{\omega C_m}}{R_2 + \frac{-j}{\omega C_m}}\right)}$$

$$simplify: \quad a = 1 + \frac{R_1}{\frac{R_2}{1 + j\omega C_m R_2}}$$

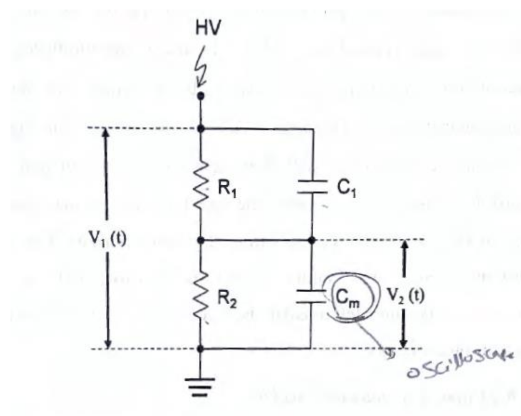


Figure 6.6: Compensated resistive potential divider

To solve this :

We add C_1 parallel with R_1 to avoid frequency dependence of voltage ratio (a)

It's value calculated

$$\frac{R_1}{R_2} = \frac{C_m}{C_1} \quad or \ \boldsymbol{R_1 C_1 = R_2 C_m}$$

But : this compensation is effective for <u>low AC or Impulse only</u>

For high voltages : the high-voltage arm will consist of many resistor elements stacked in series. In this case screened resistors are used.

SCREENING

the process of canceling or neutralizing the effect, of stray capacitances.

accomplished by surrounding the high-voltage resistor by a conducting screen maintained at the mean potential of the resistor

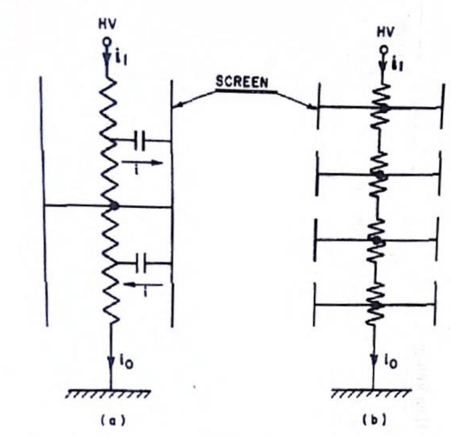


Figure 6.7: Screening process: (a) one piece. (b) subdivided.

in Direction : Capacitive currents will flow between the screen and the resistor in one direction within the upper portion of the resistor

In Opposite Direction within the lower portion. The two currents viewed from either end of the resistor, will see an effective impedance intem1ediate between the two values of in the case of unscreened resistors.

(3)

Power Losses

Capacitive potential divider

Capacitive potential dividers are therefore more suitable to use.

$$a = 1 + \frac{C_2}{C_1}$$

Sources of Error

1-Human Error

2- Instruments Errors

3-Electromagnetic noise : affect the measuring system and be superimposed on the measured signal. to reduce it :

- Signals should be transmitted via shielded coaxial cables.
- The oscilloscope may be located away from the source of noise and in a shielded room

4-The improper grounding : Grounding in high voltage laboratory should be carefully designed. (0.5 Ω)

Shielded rooms :
- walls from aluminum has sensitive layers , increase layer more sensitivity
- Grounding at 0.5 Ω
- Distance $\geq 1 - m$

	DC		AC			IMPULSE	
	mean	peak	rms	peak	waveform	peak	waveform
sphere gaps							
peak voltmeter							
Electrostatic Volt.	**rms**						
Voltage transformer							
Resistor in Series							
Resistive Devider							
Capacitive Divider							

Ch : 7

Impulses :

External origin : **Lightning** : independent of system voltage and operation

Internal origin : **switching** overvoltage : increase with increasing operating voltage

Lightening Phenomenon

Peak Charges, accumulated charge in cloud discharge (neighboring cloud or in ground)

Electrode separation: is very large 10km (cloud-cloud or cloud-ground)

- Mechanisms of charge formation is complicated, there is several theories

- During thunderstorms, positive and negative charges become separated by the heavy air currents with ice crystals in the upper part and rain in the lower parts
- cloud becomes negatively charged and has a larger layer of positive charge at its top.
- As the separation of charge proceeds in the cloud**, the potential difference** between the **concentrations of charges** increases and **the vertical, electric field along** the cloud also increases
- Notes: -
    - The total **potential difference** between the two main charge centers may vary from **10 to 100 MV** with **field gradients** ranging **from 100 V/cm** within the cloud to as high as **10 kV/cm** at the initial discharge point.
    - The energies associated with the cloud discharges can be as high as **250 kWh**· Only a part of the total charge. **, several hundred coulombs** , is released **to earth** by lightening; the **rest** is **consumed in inter-cloud discharges**.
- After charge separation in the cloud' the cloud and the ground form two plates with air as a dielectric medium.
- Since the lower part of cloud is negative , the earth is positive charged
- Lighting discharge will require breakdown in air

- In STP it requires 30 kV/cm peak but cuz of moisture content and low pressure the breakdown electric field is **10kV/cm**
- At 10kV/cm the air surrounding gets **ionized**
- a **streamer** starts from the cloud towards the earth which cannot be detected with the naked eye.
- The current in the streamer is of the order of **100 amperes** and the speed of the streamer **is 0.16 m/μ sec.**
- this called **pilot streamer** because this leads to the lightning phenomenon.
- Depending upon the state of ionization of the air surrounding the streamer, it is branched to several paths and this is known as **stepped leader fig.7.1a**
- The **leader steps** are of the order of **50 m** in length and are accomplished in about a **microsecond**
- The charge is brought from the cloud through the already ionized path to these pauses. The air surrounding these pauses is again ionized and the leader in this way reaches the earth.
- Once the **stepped leader** has made contact with the earth it is believed that a **power return stroke** (Figure 71.b) moves very fast up towards the cloud through the already ionized path by the **leader**
- This **return stroke** is very intense where the current varies between **1000:200000 Amps** at a speed of **10% of speed of light**
- It is here where the **-ve charge of the cloud is being neutralized** by the positive induced charge on the earth (Figure 7. lc). It is **this instant which gives rise to lightning flash** which we observe with our naked eye. There may be another cell of charges in the cloud near the neutralized charged cell. This charged cell will try to neutralize through this ionized path. This streamer is known as **dart leader** (Figure 7. ld).

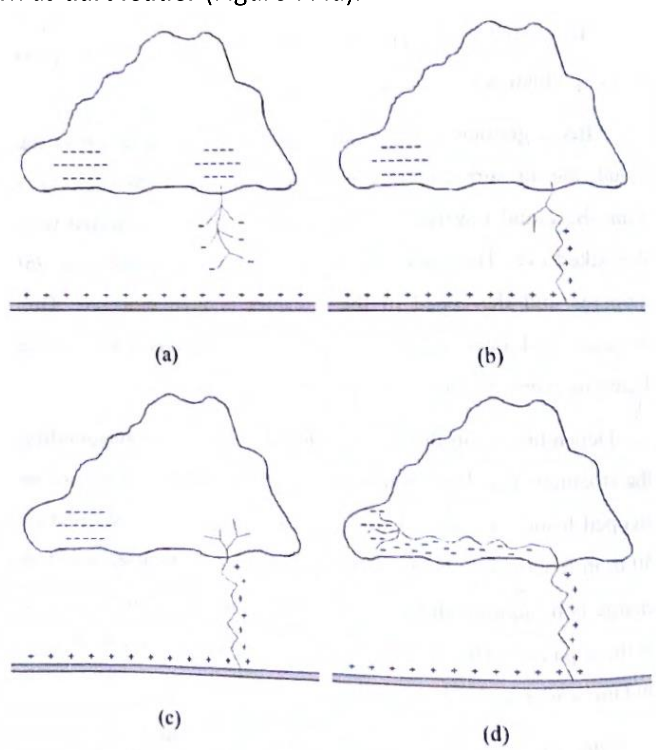


Figure 7.1: Mechanism of lightning stroke

Mechanism of discharge

1- Pilot streamer

2-Stepped leader

3-Return Stroke

4-Dart Leader

Travelling Waves

Any overvoltage surge appearing on a transmission line due to internal or external disturbances will **propagate** in the form of a traveling wave toward the ends of the line. Usually these travelling waves are high frequency disturbances and travel as waves. They may be reflected, transmitted, attenuated or distorted during propagation **until the energy is absorbed.**

Time Equation of the travelling wave

$R = Line\ Resistance\ (\Omega/m)$ $L = line\ inductance\ (H/m)$ $C = line\ capacitance - to - ground\ (F/m)$	$G = line\ loakage\ \ conductance\ (S/m)$ $dx = lenght\ of\ a\ line\ element\ (m)$

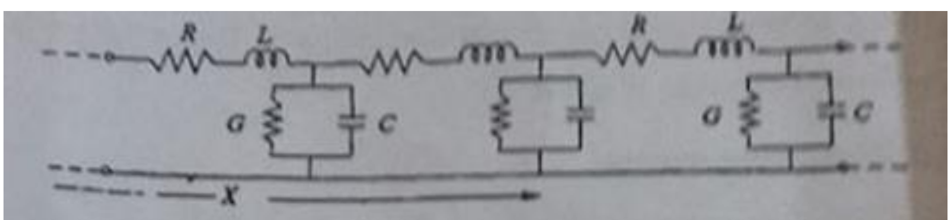


Figure 7.2: Transmission line equivalent circuit as electrical networks with uniformly distributed parameters

$$-dv = \left(Ri + L\frac{\partial i}{\partial t}\right)dx$$

$$-\ di = \left(\ Gv + C\frac{\partial v}{\partial t}\right)dx$$

$$we\ can\ negelect\ R\ and\ G$$

$$so\ ,$$

$$\frac{\partial v}{\partial x} = -L\frac{\partial i}{\partial t} \quad partial\ \ w.r.t\ \ x \rightarrow \frac{\partial^2 v}{\partial x^2} = -L\frac{\partial^2 i}{\partial x \partial t}$$

$$\frac{\partial i}{\partial x} = -C\frac{\partial v}{\partial t} \quad partial\ w.r.t\ \ t \rightarrow \frac{\partial^2 i}{\partial x \partial t} = -C\frac{\partial^2 v}{\partial t^2}$$

NOTE : (-) negative sign is due to that voltage v and current I decrease as x increases

WAVE EQUATION

Eliminate current	Eliminate voltage
$\frac{\partial^2 v}{\partial x^2} = LC\frac{\partial^2 v}{\partial t^2}$	$\frac{\partial^2 i}{\partial x^2} = LC\frac{\partial^2 i}{\partial t^2}$

It's solution

$$v(x,t) = F(x - ct) + G(x + ct)$$

To get the value of c

Second derivative of v(x,t) is

$$\frac{\partial^2 v}{\partial x^2} = \frac{\partial^2 F}{\partial x^2} + \frac{\partial^2 G}{\partial x^2}$$

Replace

$$\zeta = x - ct \qquad \therefore \frac{\partial \zeta}{\partial x} = 1$$

$$\eta = x + ct \qquad \therefore \frac{\partial \eta}{\partial x} = 1$$

$$\frac{\partial v}{\partial x} = \frac{\partial F}{\partial x} + \frac{\partial G}{\partial x} = \frac{\partial F}{\partial \zeta}\frac{\partial \zeta}{\partial x} + \frac{\partial G}{\partial \eta}\frac{\partial \eta}{\partial x} = \frac{\partial F}{\partial \zeta} + \frac{\partial G}{\partial \eta}$$

$$\frac{\partial^2 v}{\partial x^2} = \frac{\partial^2 F}{\partial \zeta^2} + \frac{\partial^2 G}{\partial \eta^2} = \frac{\partial^2 v}{\partial x^2}$$

and

$$\frac{\partial v}{\partial t} = \frac{\partial F}{\partial t} + \frac{\partial G}{\partial t} = \frac{\partial F}{\partial \zeta}\frac{\partial \zeta}{\partial t} + \frac{\partial G}{\partial \eta}\frac{\partial \eta}{\partial t} = -c\,\frac{\partial F}{\partial \zeta} + c\,\frac{\partial G}{\partial \eta}$$

$$\frac{\partial^2 v}{\partial t^2} = c^2 \frac{\partial^2 F}{\partial \zeta^2} + c^2 \frac{\partial^2 G}{\partial \eta^2} = c^2 \ \frac{\partial^2 v}{\partial x^2}$$

$$\boldsymbol{\frac{\partial^2 v}{\partial t^2}} = c^2 \frac{\partial^2 v}{\partial x^2} = \boldsymbol{c^2 \ LC \frac{\partial^2 v}{\partial t^2}}$$

$$then$$

$$c = \frac{1}{\sqrt{LC}} \quad (m/s)$$

C: the propagation velocity of the voltage and current wave along the line

---

CURRENT

$$\frac{\partial v}{\partial x} = \frac{\partial F}{\partial x} + \frac{\partial G}{\partial x} = -L \ \frac{\partial i}{\partial t}$$

$$\int \frac{\partial F}{\partial x} \ dt \ + \int \frac{\partial G}{\partial x} \ dt \ = \ -L \ \int \frac{\partial i}{\partial t} \ dt \ = \ -Li$$

Since $\frac{\partial \zeta}{\partial t} = \ -c \ amd \ \frac{\partial \eta}{\partial t} = c$

$$\therefore \ \frac{F}{-c} + \frac{G}{c} = -Li$$

$$\therefore i(x,t) = \sqrt{\frac{C}{L}} \ \ [\ F(x-ct) - G(x+ct)]$$

Function **F**	Function **G**
$\Delta x = c \ \Delta \ t \ \ \Rightarrow \ \ t \uparrow \rightarrow x \uparrow$ Forward traveling waves(refracted) $\frac{v_f}{i_f} = \sqrt{\frac{L}{C}} = Z_0 \ (chc \ imp)$	$\Delta x = -c \ \Delta \ t \ \ \Rightarrow \ \ t \uparrow \rightarrow x \downarrow$ Backward traveling waves (reflected) $\frac{v_b}{i_b} = \ -\sqrt{\frac{L}{C}} = \ -Z_0$

For overhead T.L	For underground cables
$Z_0 \ = 300{:}\, 400 \ \Omega$	$Z_0 = 30 : 80 \ \Omega$

Velocity of Wave propagation

$$c = \frac{1}{\sqrt{LC}} \quad \left(\frac{m}{s}\right)$$

$$\mathrm{L} = \frac{\mu_0}{\pi}\ln\left(\frac{2h}{r}\right) \quad and\ C = \frac{\pi\varepsilon_0}{\ln\left(\frac{2h}{r}\right)}$$

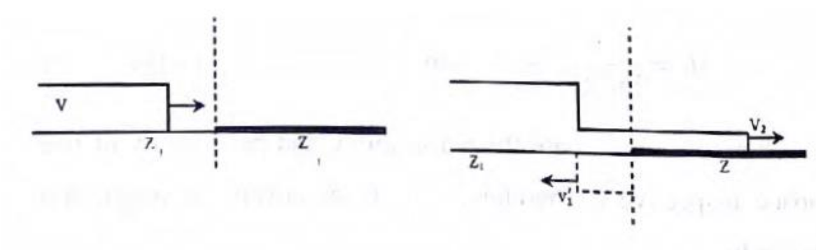
$$\therefore \boldsymbol{c} = \frac{\mathbf{1}}{\sqrt{\boldsymbol{\mu_0\varepsilon_0}}} \quad \left(\frac{\boldsymbol{m}}{\boldsymbol{s}}\right) = \boldsymbol{speed\ of\ light}$$

Independent of line geometry

But for $\epsilon_r > 1$,therefore velocity of wave propagation should be expected to be smaller than the speed of light.

Reflection and refraction of travelling waves

When the travelling wave on a transmission line reaches a point (joint – junction)beyond which the **line constants are different** like a cable connected to an overhead line,
-a part of the wave is reflected back along the line giving the reflected component
-and another part is passed on to the new section giving the refracted component.



Z_1	Z_2
$\frac{v_1}{i_1} = Z_1 \quad (\,going)$ $\frac{v_1'}{i_1'} = -Z_1 \quad (\,refelcted)$	$\frac{v_2}{i_2} = Z_2$

Kirchoff laws

$$v_1 + v_1' = v_2 \quad \& \quad i_1 + i_1' = i_2$$

$$\therefore \frac{v_1}{Z_1} - \frac{v_1'}{Z_1} = \frac{v_2}{Z_2}$$

$$so\,,final\,form$$

$$v_1' = \frac{Z_2 - Z_1}{Z_2 + Z_1} v_1 = \alpha v_1 \quad (reflected\ voltage)\ (\alpha : reflection\ coeff)$$

$$v_2 = \frac{2Z_2}{(Z_2 + Z_1)} v_1 = \beta\ v_1 \quad (refracted\ voltage\ )\ (\beta : refraction\ coeff)$$

Lattice diagram

The successive reflection of a traveling wave at the sending and receiving ends of a transmission line may lead to a buildup in the voltage or current at some points along the line.

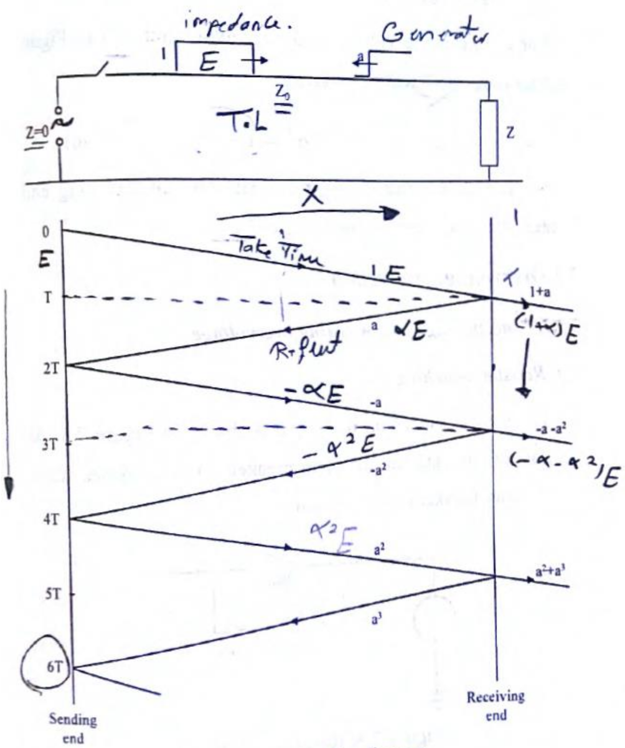


Figure 7.4: Lattice diagram

$$V\ at\ 6T\ at\ receiving\ end$$

$$V_r = 1 + \alpha - \alpha - \alpha^2 + \alpha^2 + \alpha^3 = 1 + \alpha^3$$

<u>NOTE</u> since $\alpha < 1$ then the final value of receiving end voltage after long time will be going to 1 pu

Overvoltage protection

Against **Switching**

a. <u>Resistor Switching</u>

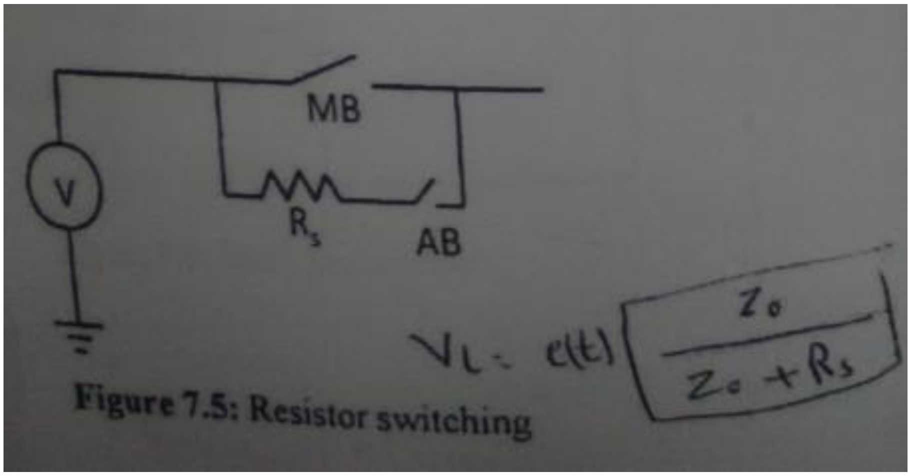


Figure 7.5: Resistor switching

At time of energization MB is opened while AB is closed

Voltage impressed at line entrance

$$V_l = e(t)\frac{Z_0}{(R_s + Z_0)}$$

R_s *depends on many factors as (system parameters, surge impedance of connected lines)*

b. <u>Phase Controlled closure</u>

- By <u>properly timing</u> of closing of CB poles, over voltage is greatly reduced
- Should be carried successively for 3 poles to reduce initial voltage in <u>three phases</u>
- <u>Difficult</u> with conventional CB , but <u>possible</u> with **Solid-state CBs**

c. <u>Use of shunt reactors</u>

- Shunt compensation to improve the performance of the line, which otherwise will draw large capacitive current from supply
- Additional advantage : reducing energization surge magnitudes , accomplished by reduction temporary overvoltage

d. **Drainage of trapped charges**

Charges are trapped on capacitance to ground of transmission lines after their sudden re-energization

If the line is reenergized soon after, usually by means of automatic reclosures, these charges may cause an increase in the resulting surge

- So, trapped charges may be partially drained through the switching resistors incorporated in circuit breakers.

Against **Lighting overvoltage**

a. **Spark gap arresters**

- use sphere gaps, when overvoltage occurs, exceeds the BD strength of sphere gap
- break down occurs so the overvoltage discharges through it to goriund
- it's used near important equipment such as (substations)

Disadvantages

1- The time lag that occurs before the gap sparks over.
2- The variation of the spark overvoltage with the polarity and surrounding condition gaps.
3- The current continues even after the overvoltage has disappeared causing a line to ground short circuit on the network.

b. **Metal-Oxide surge arresters**

- ceramic material can be used to make resistors with a much higher degree of non-linearity over a large current range.
- Current Voltage relationship $I = cV^{\alpha}$

$$\alpha > 20$$

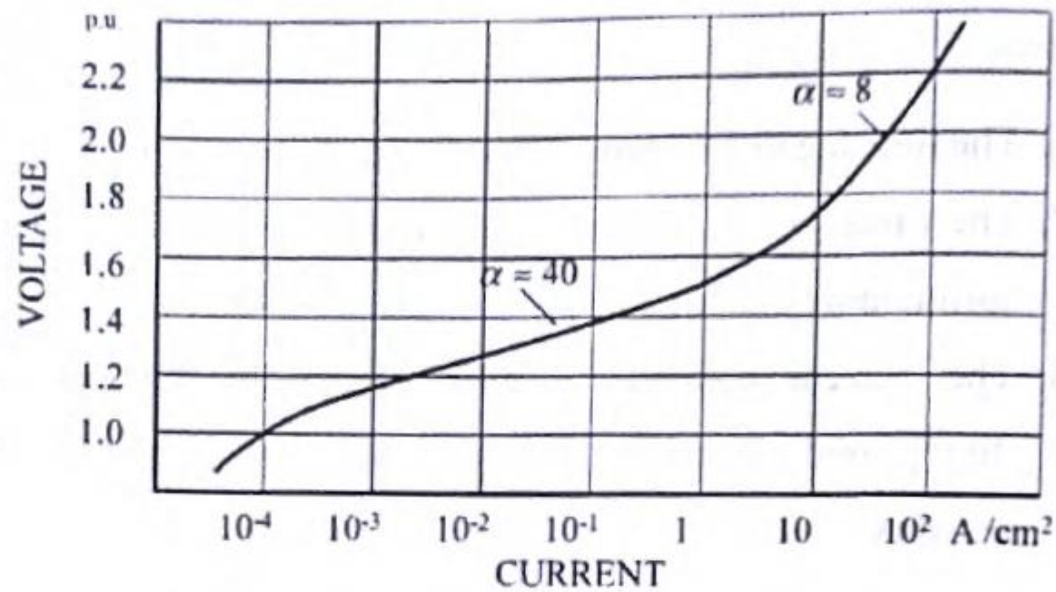


Figure 7.7: A typical characteristic of Metal-oxide surge arresters

When an overvoltage occurs, the current will rise according to the characteristic of Figure 7. 7. At the end of the voltage transient the current is reduced

Advantages:

1- Very simple construction
2- Rapid operation
3- No arc and No follow current after surge absence

c. **<u>Zinc Oxide varistos(ZnO)</u>**

- semiconducting ceramics having highly non-linear current-voltage characteristics. Therefore, they act as voltage-dependent switching devices as shown
- The resistivity of a ZnO varistor is very high (more than $10^{10}\Omega$.cm) below a certain threshold voltage (V_{th}), whereas it is very low (less than several Ω .cm) above the threshold
- $\alpha = 30 : 100$
- <u>the dielectric property.</u> Below the threshold voltage, ZnO varistors are highly capacitive.

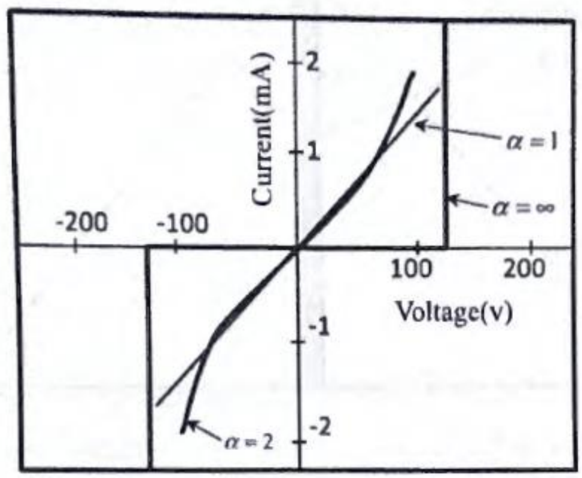


Figure 7.8: Current-voltage characteristics of a typical Zinc oxide varistor

d. **Lightning rods and wires**

- Lightning rods are used to protect long structures and buildings from lightning strokes
- Lightning rod consists of a metallic rod mounted on the top of the building and it is electrically connected to the ground through an electrode
- Protection zone of lightning rod is the **zone covered** by an angle of **45°** as shown in Figure 7.9. There are several calculations used for obtaining lightning rod length and distribution.

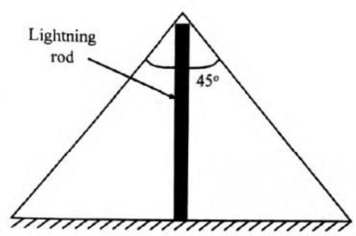


Figure 7.9: Lightning rod and its protection zone

For power TL : a ground wire is suspended on the upper points of towers in order to protect from lightning as shown in Figure 7.10.

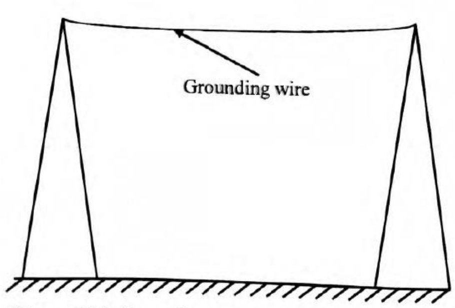


Figure 7.10: Grounding wire over a transmission line